

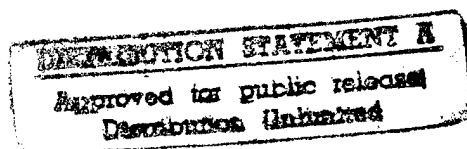


**US Army Corps
of Engineers**
Walla Walla District

A Review of Literature Related to Movements of Adult Salmon and Steelhead Past Dams and Through Reservoirs in the Lower Snake River

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**U.S. Fish and Wildlife Service
Idaho Cooperative Fish and Wildlife
Research Unit**



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IN THE LOWER SNAKE RIVER**

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U.S. Army Corps of Engineers
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Abstract

A synthesis of published and unpublished literature on the upstream migration of adult salmon and steelhead *Oncorhynchus mykiss*, with particular reference to passage through reservoirs and over dams, was prepared as part of an evaluation of fish passage through the lower Snake River. Most of the information on adult migrations in the Snake and Columbia rivers was collected on chinook salmon *O. tshawytscha* and steelhead. The amount of flow, temperature and turbidity of the water, and partial barriers are natural factors that affect the rate of migration and survival of upstream migrants. Human-caused alterations in flow, temperatures, and turbidities through the construction of dams and creation of reservoirs may be beneficial or detrimental to migrants, depending on the amount of change from natural and the fishes' ability to adapt. Dams and reservoirs placed in the migration path of adult salmon and steelhead usually create unique passage problems because the structures and discharges differ and the stocks of fish involved change from one section of the river to the next.

Survival rates of adult salmon and steelhead in the Snake and Columbia rivers were not assessed before the construction of dams, but some information on migration rates was obtained. In free-flowing rivers, salmon have been observed migrating at rates up to 24 km/d (15 mi/d). Lesser rates of migration have been observed when rivers were turbid and in winter when steelhead suspend their migration till spring. Migration rates in reservoirs ranged from 16 km/d for fall chinook salmon in Brownlee Reservoir, a large storage pool, to 56 km/d for spring chinook salmon in Ice Harbor and Little Goose reservoirs, run-of-the-river pools.

The time required for adult salmon and steelhead to migrate past dams varies with the structure, flow, spill, powerhouse discharge, turbidities, and the positioning of fishway entrances. Some fish approach and pass over a dam in less than a day, but the average reported time to pass a dam has ranged from 1 to 5 d in several studies. Passage rates are slower when there are high flows and spills that make it difficult for fish to find fishway entrances.

The fishways used by adult fish and the rate of passage is influenced by the distribution of discharge from a dam and the effectiveness of the attraction flows at the fishway entrances. When there is little or no spill, few fish use the fishway entrances near the spillway. Small amounts of spill have been shown to increase use of entrances near spillways, but large amounts of spill can completely block some fishway entrances to fish use.

Discharges from the powerhouse can vary widely depending on the flow in the river and power demand. During high flows all turbines may be running at capacity, but at lower flows only 1 or 2 turbines may be used at the Snake

River dams. The preferred turbines to operate for optimum fish passage has been studied at some dams, but not well defined in a way that can be universally applied. If passage problems occur at a dam, then site specific studies will probably be required.

Hydroelectric power peaking can affect adult fish migrating past dams through daily changes in discharge and by the volume of discharge during periods of peak power production. Rates of discharge change did not seem to affect fish entry into the fishways, but passage rates were lower during peak discharge periods than at lower discharge rates, presumably because the high discharges made the fishway entrance attraction flows less efficient. The effect on fish of reducing discharges from selected dams to zero at night to conserve water for daytime power production has not been settled. Although fish are believed to move less at night, and would, therefore, be minimally affected by no flow through the reservoirs at night, the results of two studies are in conflict. A more extensive study of zero flow at night in the lower Snake River is underway.

High volume spills at dams can delay fish in finding fishway entrances and lead to mortality. General guidelines for shaping the pattern of spill at each of the dams have been developed from site specific studies. Testing of spill and powerhouse discharge patterns has not been conducted at all dams because of the cost and unreliable nature of spring runoff flows.

Considerable study has gone into the location and structure of fishway entrances. Fishway entrances on either bank of the river, flanking the spillway, and along the powerhouse appear to give fish sufficient opportunities to enter fishways, except perhaps, when high flows create currents that obscure some entrances from the fish. Entrance size and depth, and discharges from the entrances appear adequate if attraction flows are good enough to lead the fish to the entrances. Fish can exit, as well as enter, the fishways at the entrances, and enough fish do so at some entrances to have a net entrance rate of zero or less. The extent of the problem is under study at the lower Snake River dams and a fishway fence designed to discourage fish from exiting certain entrances is being tested.

Once fish enter the fishways, passage is relatively rapid, usually a matter of a few hours, except that most fish move through the fishways during daytime. Fishways with 1:10 slopes, vertical baffles, overflow weirs with submerged orifices, and velocities less than about 1 m/s allow the fish to ascend with minimal delays. A few fish have been observed to partially ascend and then move down and even exit fishways, before eventually reascending. Instances of fish taking a long time to pass through a fishway often involve up and down

movements, and may be related to other factors such as turbidity and gas supersaturation.

The rate of fallback over a dam by adult salmon and steelhead varies with flow and spill, by dam, and species. Spring and summer chinook salmon have the highest fallback rates (up to 30+%), particularly at dams with limited powerhouse capacity, because they migrate upstream during the spring runoff. The location of fishway exits in relation to the spillway is an important factor at some dams. Fallback rates can also be high for steelhead (up to 20+%) at some dams that are in the overwintering areas of the mid Columbia and lower Snake rivers. Mortality rates of fallback fish have not been well documented, but a high percentage of tagged fish have been observed reascending dams.

Water temperatures influence the rates of migration of steelhead and salmon. High water temperatures have slowed the migrations of fall chinook salmon and steelhead into the Snake River during August and September, and perhaps affected the migration rates in the lower Columbia River. Steelhead also slow their migration in late fall as water temperatures decline and they do not resume their migration to the spawning grounds until the following spring when temperatures increase from the winter lows.

High concentrations of dissolved nitrogen were a persistent problem in the lower Snake River before all six turbines were installed at each dam and "flip-lips" to prevent deep plunging of spilled water were installed in the spillways. Nitrogen supersaturation at problem concentrations can occur when river flows exceed the capacity of the powerhouses and the volume of spill (more than about 60 kcfs) makes the flip-lips ineffective.

A portion of the adult salmon and steelhead migrating to spawning grounds and hatcheries die enroute, and those losses can be both natural and human-caused. Discrepancies between counts of fish at dams have been relatively large in some instances, which has raised the concern about extraordinary losses at some dams. Some of the discrepancies have been caused by high fallback rates with subsequent reascension at specific dams, and some can be accounted for as fish caught by fishermen, fish spawning in the main stem rivers or entering tributaries. However, significant portions of the discrepancy cannot be accounted for in some areas and they may in fact be losses of fish to a variety of causes. Discrepancies between counts of steelhead at McNary, Priest Rapids, and Ice Harbor dams have been large in some years and have not been accounted for fully, an indication, that significant losses may occur in some years, mostly among fish destined to enter the Snake River. Discrepancies in counts of salmon and steelhead between the four Snake River dams and losses in radio tracking studies have been relatively low.

Introduction

Literature (published and unpublished articles) on the passage of adult salmon and steelhead *Oncorhynchus mykiss* at dams and through reservoirs was collected, reviewed, and this synthesis was prepared as part of a study of the passage of adults through the reservoirs and past the dams in the lower section of the Snake River (Figure 1). The literature review, and an analysis of existing data for the lower Snake River (Bjornn and Rubin 1992), and field studies started in 1991 were undertaken as part of the U.S. Army Corps of Engineers research program to determine if there was evidence of unusual delays or losses at the four dams in the lower Snake River. In the field studies, the effects of zero-flow at night, various spill patterns, preferences for fishway entrances, a fence in the fishways to reduce fishway fallout, and fallback over the dams were to be evaluated.

Literature on the migration of adult salmon and steelhead was collected by first searching literature databases for references, collecting articles, checking the articles for additional references, and finally searching agency files for copies of unpublished reports. Personnel of the Corps of Engineers, Oregon Department of Fish and Wildlife, and National Marine Fisheries Service were especially helpful in securing copies of unpublished reports from their files. The Office of Information Transfer of the U.S. Fish and Wildlife Service searched databases and provided a list of references. More than 600 articles were screened for information on the upstream migration of adult salmonids, and many of those are included in the list of literature cited or the list of additional references that have information relative to passage at dams and through reservoirs.

Study Area and Fish of Concern

Three populations of adult chinook salmon *O. tshawytscha* and two of steelhead enter the Snake River (Figure 1) each year on their way to spawning grounds and hatcheries in the tributaries. In earlier years, significant numbers of coho salmon *O. kisutch* and sockeye salmon *O. nerka* entered the Snake River; the former have been declared extinct, and the latter are in such low abundance that they have been listed as endangered under the Endangered Species Act. Chinook salmon destined to spawn in the Snake River basin, which have been listed as threatened, enter the Columbia River starting in March and continue through October. The three populations or runs are

referred to as spring, summer, and fall chinook salmon based on the time they enter the Columbia River. The spring chinook salmon enter the Columbia River during March, April, and May. They cross Bonneville Dam from mid March through the end of May, and Ice Harbor Dam about two weeks later (Figure 2). The summer chinook salmon enter the river during late May, June, and July, pass Bonneville Dam during June and July, and pass Ice Harbor Dam from mid June to mid August. The third group, or fall chinook salmon, enters the river starting in August and passes Bonneville Dam primarily during late August, September, and early October.

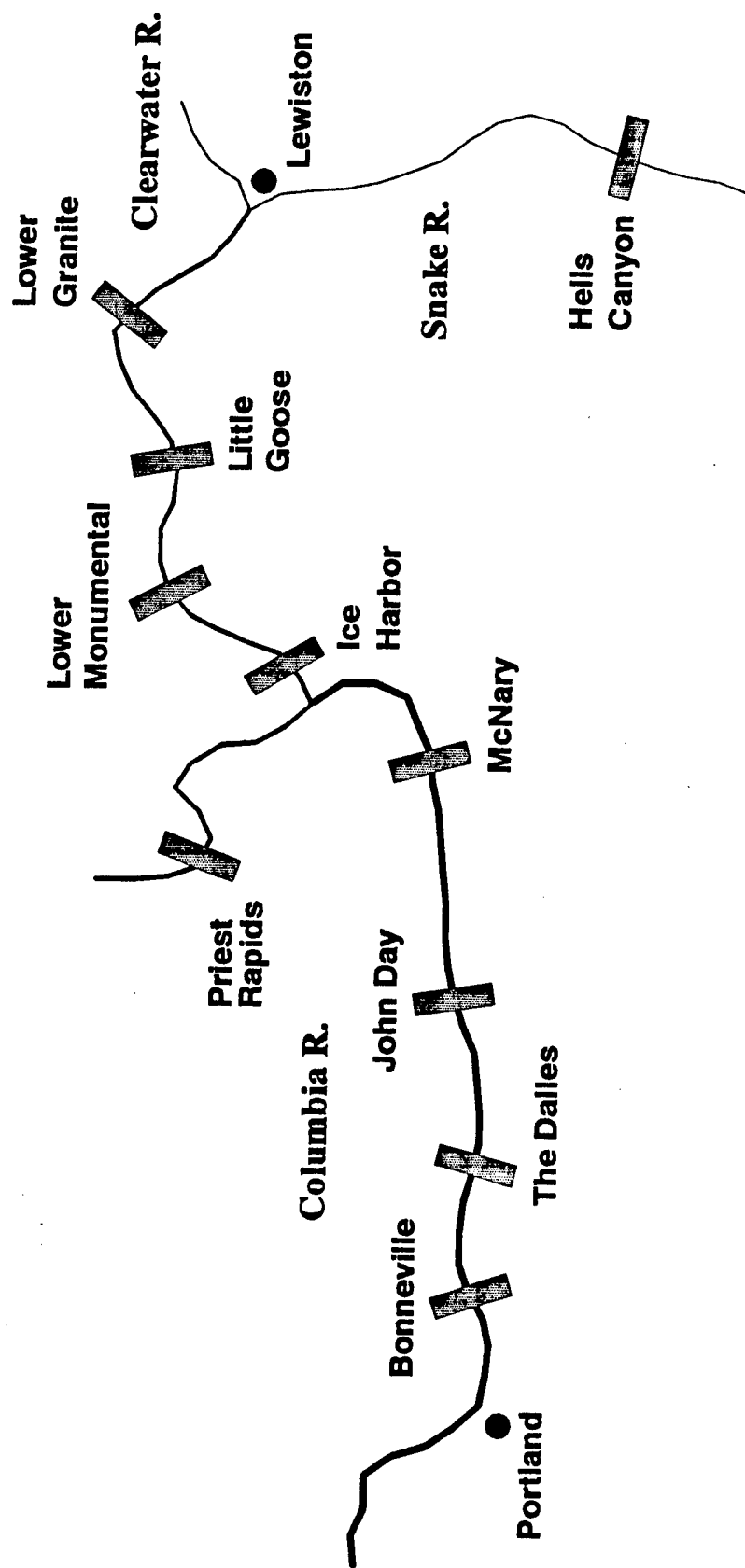


Figure 1. Map of the Columbia River basin with the location of dams in the Columbia and Snake Rivers.

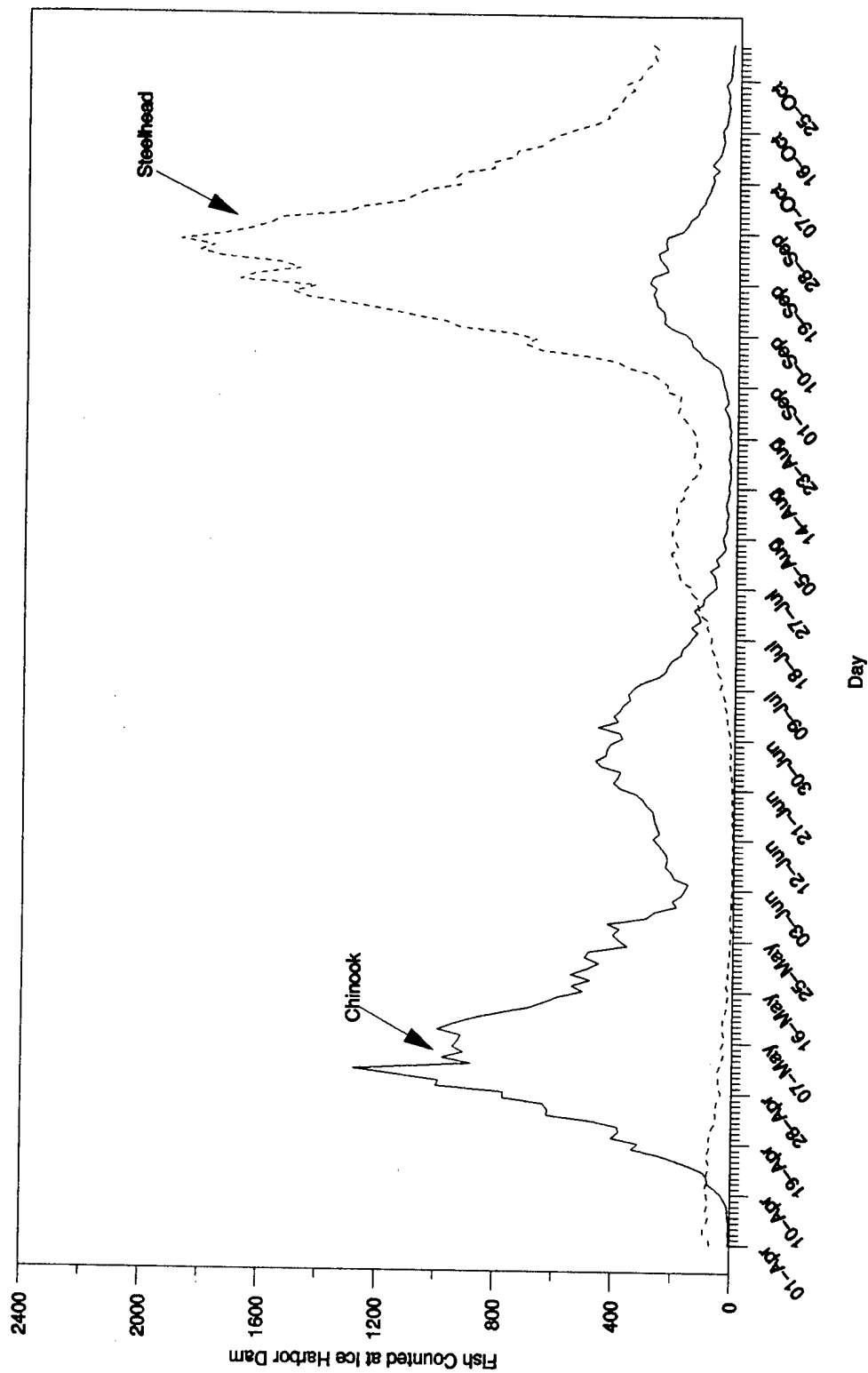


Figure 2. Mean daily counts of chinook salmon and steelhead at Ice Harbor Dam on the Snake River, 1962-1989.

The fall run passes over Ice Harbor Dam in September and early October (Figure 2).

Each of the three runs of chinook salmon (spring, summer, and fall) entering the Snake River are made up of many separate stocks of fish that maintained their identity and genetic integrity in the past by spacial or temporal separation during spawning. The spring and summer chinook salmon spawned in the tributaries to the Snake River, while the fall chinook salmon spawned mainly in the main stem Snake River, with a few fish spawning in the lower ends of a few major tributaries. In some of the tributaries, either spring- or summer-run fish used the stream, but in others, fish of both runs spawned. In streams where fish of both runs were present, the spring chinook salmon arrived first, spawned first, and usually spawned upstream from the summer chinook salmon.

Steelhead that spawn in the tributaries of the Snake River enter the Columbia River beginning in June and continue through October. The steelhead are termed summer steelhead because of their time of return to freshwater. The Snake River steelhead are further divided into two groups, the A-group that enters the Columbia River first and passes over Bonneville Dam from June through late August, and the B-group that enters later and passes Bonneville Dam from late August through October. The A-group fish are smaller than similar age class B-group fish because they spend fewer months in the ocean in the year they return to the river. The two groups of fish proceed up the Columbia River and some of the A-

group fish enter the Snake River as early as July. Most of the steelhead, however, do not enter the Snake River until September because of high river temperatures, and the A- and B-group fish are mixed together by the time most of them enter the Snake River in fall (Figure 2).

In the Snake River basin, the A-group steelhead were historically produced in the lower elevation tributaries (Tucannon River, lower and smaller tributaries of the Clearwater and Salmon Rivers, Grande Ronde River, Imnaha River, tributaries upstream from the mid Snake River dams, and spring fed streams such as the Lemhi and Pahsimeroi Rivers) where snowmelt runoff was often in March and April. The fish spawned in April. The B-group steelhead were historically produced in the larger high elevation tributaries of the Clearwater and Salmon Rivers (North and South Forks of the Clearwater River, Lochsa and Selway Rivers, South and Middle Forks of the Salmon River, and the upper Salmon River near Stanley) where snowmelt runoff peaked in late May or June. The fish usually spawned in late April and May.

Sockeye salmon destined for the Snake and upper Columbia basin streams enter the Columbia River in early summer, pass over Bonneville Dam primarily during June and July, and pass over McNary Dam in the latter half of June, July, and August. Sockeye salmon entering the Snake River crossed over Ice Harbor Dam in late June and July. In years of relatively large runs into the Snake River (1963 and 1964), some fish passed over Ice Harbor

Dam in September and October, but the destination of those fish is unknown. Sockeye salmon migrating to Redfish Lake at the head of the Salmon River in Idaho arrived primarily during August (Bjornn et al. 1968) and were the fish that passed over Ice Harbor Dam in July.

In the following sections we present the information we have found on the

Factors Influencing Migrations

Many factors, both natural and human-caused, can influence the migration of adult salmon and steelhead as they migrate from the ocean to spawning areas. Flow, turbidity, and temperatures in the rivers vary seasonally and from year to year (Figure 3), and may delay the fish's migration when those factors are unsuitable. Most indigenous stocks, however, have adapted to the variations in the natural environment. For example, adult salmon and steelhead migrating to spawning areas in the upper Columbia River basin have incorporated enough flexibility in their schedules to allow for delays caused by naturally occurring high turbid flows in spring or temporarily unsuitable temperatures in the fall. The normal range of delays did not prevent them from arriving at the spawning areas on schedule.

Human-caused factors that may affect the upstream migration of adult salmon and steelhead include alteration of flows, temperatures, and water quality, the placement of dams in the rivers, and the creation of reservoirs. When human activities increase the length of delays in migration or create conditions that are

migrations of adult salmon and steelhead relative to their passage over the dams and through the reservoirs in the lower Snake River. We have organized the sections from the fishes' perspective of migrating upstream and discuss the various factors that might affect their migration.

more hazardous than normal, then the environmental variations can affect the fish deleteriously. The creation of storage reservoirs in the Snake basin has reduced the peak flows in spring, a change that may aid adult migration past dams. Creation of the four lower Snake River reservoirs may have altered the temperature patterns in the river at its confluence with the Columbia River by creating a larger water mass that would cool slower in the fall. Turbidity of the spring runoff has probably increased with increased land use in the basin, but turbidity at the Snake River mouth may be lessened by sedimentation in the four reservoirs. The dams are obstacles to migration unless the fish can find the fishway entrances and move through the fishways without undue delay. The volume and pattern of discharge from the powerhouses and spillways has an effect on the ability of fish to find fishway entrances. Reservoirs have replaced the river in the lower stretch of the Snake River, but they seem to have little effect on the upstream migration of adults.

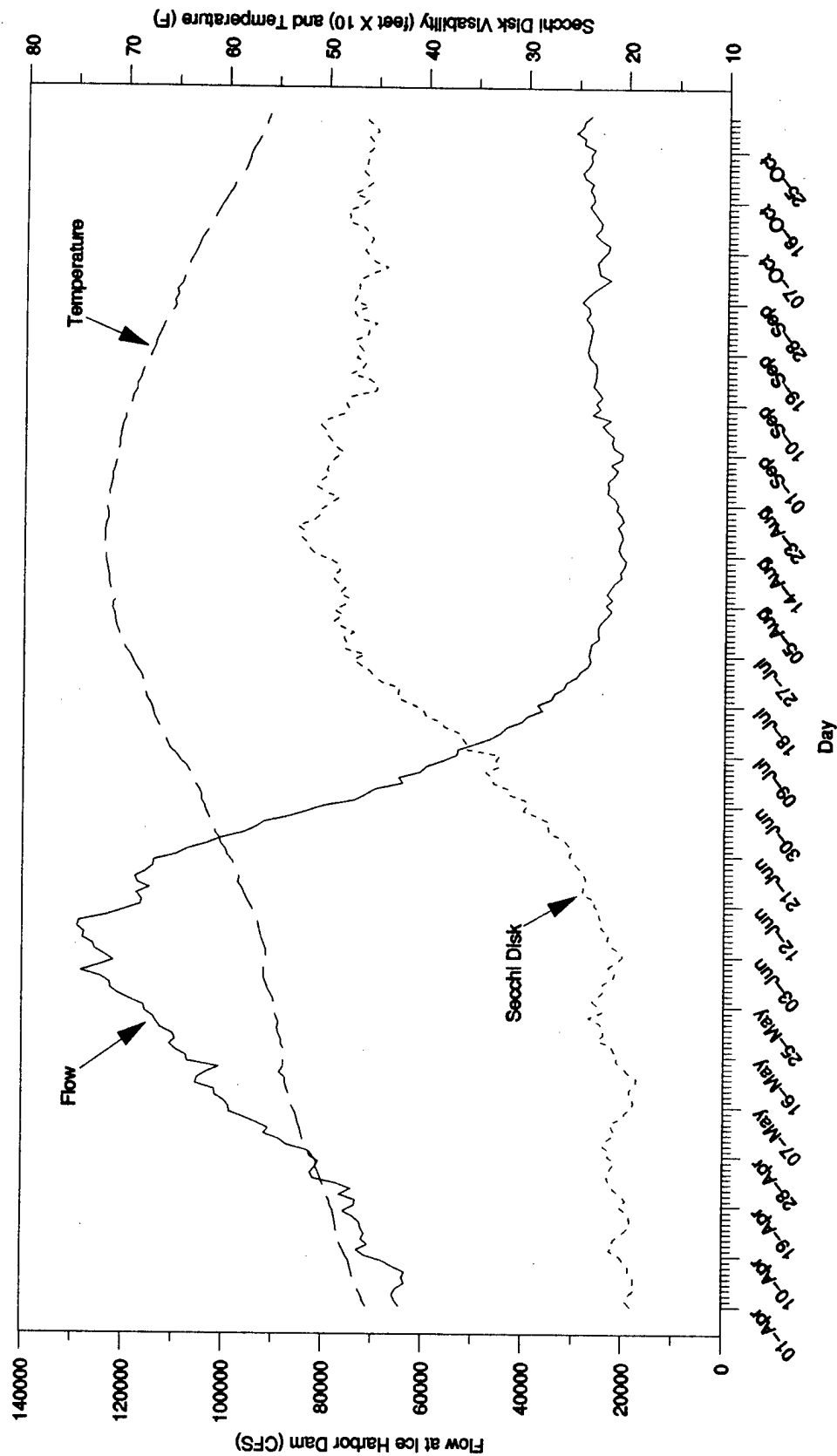


Figure 3. Mean daily flow, water temperature, and secchi disk visibility of the Snake River at Ice Harbor Dam, 1962-1989.

Migration in Natural Rivers

Adult salmon and steelhead have migrated up the Columbia and Snake rivers for thousands of years and had adapted to the natural seasonal cycles and variations in flows and temperatures. Natural rates of upstream migration vary and depend on the species, stock, destination, and season of the year. Migration rates of salmon and steelhead moving up the Columbia and Snake rivers have been measured directly in a number of studies, and incidentally observed in several other studies (Table 1).

In general, chinook salmon migrated upstream in the unimpounded Snake River and its tributaries at rates of 20-24 km/d during spring and summer, steelhead at rates of 10-16 km/d when actively migrating in summer, early fall, or spring, but they had periods of almost no movement in late fall and winter, and sockeye salmon migrated at rates of 19 km/d in summer (Table 1). The path of migration in the rivers for chinook and sockeye salmon was not reported, but steelhead in the Snake River were most often found within 20-30 m of shore and near the bottom.

The earliest study of migration rates in unimpounded Snake basin streams was reported by the Oregon Fish Commission (1960b). Adult salmon and steelhead were collected and tagged at Lewiston, Idaho (5,824 chinook salmon, 5,273 steelhead, and 540 sockeye salmon) in 1954-1957 and recovered in fyke nets at upstream locations, from spawning grounds, and from the sport fishery. Chinook salmon recovered in upstream fyke nets averaged migration rates of 20.9 and 24.1 km/d in

1955 and 1956, respectively. Chinook salmon caught in the sport fishery averaged migration rates of 17.7 km/d in 1954, and 19.3 km/d in 1956 and 1957. Steelhead averaged 16.1 and 11.3 km/d during the spring, and 9.7 and 8.0 km/d in the fall for the 1954-55 and 1955-56 fish runs, respectively. Sockeye salmon averaged 19.3 km/d to a weir more than 600 km upstream (Redfish Lake). In another early study (1955 and 1956) before dams were constructed in the lower Snake River, Burck and Jones (1963) released 1,786 steelhead at McNary Dam to measure migration rates. Eighty-one steelhead were recovered at Lewiston Dam, 283 km upstream. The 30 fish tagged in January migrated at an average rate of 3.2 km/d, 17 fish tagged in February averaged 3.9 km/d, and the 34 fish tagged in April averaged 12.2 km/d. The steelhead tagged in the winter probably moved little or none until spring.

The effect of season and cold water temperatures on steelhead migration rates was demonstrated by Falter and Ringe (1974) while tracking 84 steelhead with radio transmitters through the Snake River upstream from the Lower Granite Dam site in 1969, 1970, and 1971. From July to early September, the steelhead moved at relatively constant rates 24 hours a day.

As the temperatures decreased from 21°C to 3°C in the fall, the migration rate decreased. Rates of 10.7 to 16.7 km/d were measured in the summer and early fall, but as low as 0.5 km/d in the late fall for steelhead migrating from the Lower Granite Dam site to the Snake-Clearwater confluence. The steelhead generally

Table 1.-Salmon and steelhead migration rates in the Columbia River Basin. Rates are kilometers/day unless otherwise shown. Passage times are given when appropriate.

Species	Location	Migration rate	Source	Comments
Free flowing rivers				
Coho	Bonneville to McNary Dam	19.5	Oregon Fish Comm. 1960a	Before The Dalles Dam
Sockeye	Bonneville to Rocky Reach	28.4	Raymond 1964	From 1938-50 dam counts
Sockeye	Upper Salmon River	19.3	Oregon Fish Comm. 1960b	To Redfish Lake
Steelhead	Upper Snake/Salmon Rivers	11.3-16.1	"	Spring 1954-56
Steelhead	Upper Snake/Salmon Rivers	8.0-9.7	"	Fall 1954-56
Steelhead	McNary Dam to Lewiston Dam	3.2-3.9	Burck & Jones 1963	Jan. & Feb. 1956
Steelhead	McNary Dam to Lewiston Dam	12.2	"	April 1956
Steelhead	Lower Snake River	10.7-16.7	Falter & Ringe 1974	Summer 1970
Steelhead	Lower Snake River	0.0-0.5	"	Winter 1970-71
Steelhead	Lower Snake River	11.0	Stabler et al. 1981	Before Lower Granite Dam
Chinook	Upper Snake/Salmon Rivers	17.7-24.1	Oregon Fish Comm. 1960b	1955-56
Reservoirs				
Steelhead	Rocky Reach Reservoir	1.6	Strickland 1967b	1965
Steelhead	Ice Harbor Reservoir	1.3 km/h	Strickland 1967a	1967
Steelhead	Ice Harbor Reservoir	1.3 km/h	Eldred 1970	1969
Steelhead	Ice Harbor Reservoir	12.8	"	1969
Steelhead	Bonneville Reservoir	1.3 km/h	Liscom et al. 1978	Spring 1977
Steelhead	McNary to Ice Harbor Dam	5.5-6.6	Bjornn & Ringe 1980	1978
Steelhead	Lower Monumental Reservoir	0.9 km/h	Liscom et al. 1985	Summer, water temp. ≤ 21 C
Steelhead	Lower Monumental Reservoir	0.3 km/h	"	Summer, water temp. > 21 C

Table 1. Continued.

Species	Location	Migration rate	Source	Comments
Chinook	Brownlee Reservoir	16.1-16.8	Trefethen, Sutherland 1968	1960, 1962
Chinook	Bonneville Reservoir	25.3	Weiss 1970	Spring & summer
Chinook	Bonneville Reservoir	25.7-35.4	Monan & Liscom 1973	Low flows, 1972
Chinook	Bonneville Reservoir	12.9	"	High flows, 1972
Chinook	Bonneville Reservoir	21.0	Young et al. 1975	Spring 1974
Chinook	Bonneville Reservoir	12.0	"	Summer 1974
Chinook	Little Goose Reservoir	1.6 km/h	Liscom & Monan 1976	Spring 1975
Chinook	Bonneville Reservoir	2.5	Monan & Liscom 1976	Includes one steelhead
Chinook	Ice Harbor Reservoir	11.1-35.6	McMaster et al. 1977	1975-76
Chinook	Lower Monumental Reservoir	35.6-49.7	"	1975-76
Chinook	Bonneville Reservoir	1.6 km/h	Liscom et al. 1978	Spring 1977
Chinook	Bonneville Reservoir	17.8	Gibson et al. 1979	Summer chinook, 1978
Chinook	Lower Monumental Reservoir	2.0-5.0 km/h	Haynes & Gray 1980	1976-77
Chinook	Lower Granite Reservoir	0.5-1.12 km/h	Stabler et al. 1981	1976
Chinook	Little Goose Reservoir	56.3	Turner et al. 1983	Median rate, 1981
Chinook	Ice Harbor Reservoir	56.0	Turner et al. 1984	Median rate, 1982
Chinook	Lower Monumental Reservoir	1.4-1.5 km/h	Liscom et al. 1985	1981
Reservoirs and dams				
Sockeye	Bonneville to Rocky Reach	25.3	Raymond 1964	From 1951-63 dam counts
Sockeye	Bonneville to McNary Dam	27.8	"	Past The Dalles Dam
Sockeye	Bonneville to Rocky Reach	16.0-32.0	Horton & Wallace 1966	1966
Steelhead	Bonneville to Little Goose	8.2-20.4	"	Decreased with season
Steelhead	Ice Harbor to Little Goose	9.6-12.6	"	Fall 1975
Steelhead	Ice Harbor to Lower Granite	7.8-10.4	Bjornn & Ringe 1980	Past Lower Monumental & Little Goose Dams

Table 1. Continued.

Species	Location	Migration rate	Source	Comments
Chinook	Bonneville to McNary Dam	25.9-27.2	Oregon Fish Comm. 1960a	Summer & Fall
Chinook	Bonneville to McNary Dam	18.0	Young et al. 1974	Spring chinook, 1973
Chinook	Bonneville to McNary Dam	20.0	"	Fall chinook, 1973
Chinook	Ice Harbor to Little Goose	8.4-20.4	McMaster et al. 1977	Past Lower Monumental Dam
Chinook	Bonneville to Little Goose	21.6	Gibson et al. 1979	Low flows, 1973
Chinook	Bonneville to Little Goose	14.7	"	High flows, 1973-74
Past dams				
Sockeye	Bonneville Dam	53.3 hrs	Ross 1983	Median rate
Steelhead	Bonneville Dam	38.0 hrs	Monan & Liscom 1976	1975, four fish
Steelhead	Bonneville Dam	59.0 hrs	Liscom et al. 1978	1977, average delay
Steelhead	The Dalles Dam	1.9 hrs	"	1977, average delay
Steelhead	John Day Dam	63.0 hrs	"	1977, average delay
Steelhead	Bonneville Dam	37.6 hrs	Ross 1983	Summer steelhead, median
Steelhead	Bonneville Dam	16.8 hrs	"	Fall steelhead, median
Steelhead	Bonneville Dam	9.1 hrs	Turner et al. 1984	Fall, median rate
Steelhead	Little Goose Dam	17.3-22.8 hrs	Liscom et al. 1985	1981
Chinook	Bonneville Dam	101-181 hrs	Monan & Liscom 1973	Spring 1972
Chinook	The Dalles Dam	23-39 hrs	"	Spring 1972
Chinook	Lower Monumental Dam	42.0 hrs	Monan & Liscom 1974b	Spring 1973, 39.2 kcfs
Chinook	Lower Monumental Dam	84.3 hrs	"	Spring 1973, 79.6 kcfs
Chinook	Bonneville Dam	1-2.0 days	Young et al. 1974	Spring 1973
Chinook	The Dalles Dam	0.5-1.0 days	"	Spring 1973
Chinook	Bonneville Dam	60.0 hrs	Monan & Liscom 1975	Spring 1974
Chinook	Bonneville Dam	47.0 hrs	"	Summer 1974

Table 1. Continued.

Species	Location	Migration rate	Source	Comments
Chinook	Lower Granite Dam	78 hrs	Liscom & Monan 1976	Spring 1975
Chinook	Bonneville Dam	37.0 hrs	Monan & Liscom 1976	Summer 1975
Chinook	The Dalles Dam	40.5 hrs	"	Summer 1975
Chinook	Bonneville Dam	56.0 hrs	Liscom et al. 1977	Spring 1976
Chinook	Bonneville Dam	48.0 hrs	Liscom et al. 1978	Spring 1977
Chinook	The Dalles Dam	15.0 hrs	"	average delay
Chinook	John Day Dam	45.0 hrs	"	average delay
Chinook	Bonneville Dam	50.8 hrs	Johnson et al. 1979	Spring 1978, median
Chinook	Bonneville Dam	49.4 hrs	"	Fish that fellback
Chinook	Little Goose Dam	216, 90 hrs	Haynes & Gray 1980	1976, 1977
Chinook	Lower Granite Dam	50, 58 hrs	"	1976, 1977
Chinook	John Day Dam	82.6, 81.9 hrs	Johnson et al. 1982	1979, 1980, median
Chinook	The Dalles Dam	14 hrs	Liscon, Stuehrenberg 1983	East ladder, median
Chinook	John Day Dam	31 hrs	"	Fall chinook
Chinook	McNary Dam	14 hrs	"	Fall chinook
Chinook	Bonneville Dam	27.7 hrs	Ross 1983	Spring, median rate
Chinook	Bonneville Dam	16.2 hrs	"	Summer, median rate
Chinook	Bonneville Dam	18.3 hrs	"	Fall, median rate
Chinook	Little Goose Dam	53.4 hrs	Turner et al. 1983	Spring 1981, median
Chinook	Lower Granite Dam	52.5 hrs	"	Spill <25 kcfs
Chinook	Lower Granite Dam	197.0 hrs	"	Spill >25 kcfs
Chinook	Ice Harbor Dam	118.3 hrs	Turner et al. 1984	Spring 1982
Chinook	Lower Monumental Dam	44.8 hrs	"	Spring 1982
Chinook	Bonneville Dam	35.5 hrs	Turner et al. 1984	Spring 1983, median
Chinook	Bonneville Dam	20.4 hrs	"	Fall 1983, median
Chinook	Bonneville Dam	17-28.0 hrs	Shew et al. 1988	1st powerhouse, median
Chinook	Bonneville Dam	28.6-31.4 hrs	"	2nd powerhouse, median

Table 1. Continued.

Species	Location	Migration rate	Source	Comments
Chinook	John Day Dam	38.3 hrs	"	Spring 1984, median
Through fishways				
Sockeye	McNary Dam	2.4 min/pool	U.S. Army Corps 1961	Oregon ladder, 58 pools
Sockeye	Rocky Reach Dam	1.6-1.8 days	Major & Paulik 1972	1964-65
Sockeye	Bonneville Dam	2.9-5.8 hrs	Ross 1983	1982, days
Sockeye	McNary Dam	2.9 hrs	Shew et al. 1985	Spring 1985
Steelhead	Bonneville Dam	6.0 hrs	Monan & Liscom 1976	Summer 1975
Steelhead	Bonneville Dam	2.7-4.2 hrs	Ross 1983	Summer 1982, days
Steelhead	Bonneville Dam	11.5-17.2 hrs	"	Summer 1982, nights
Steelhead	Bonneville Dam	2.5-3.7 hrs	"	Fall 1982, days
Steelhead	Bonneville Dam	16-27.8 hrs	"	Fall 1982, nights
Steelhead	Bonneville Dam	2.4-3.4 hrs	Turner et al. 1984	Fall 1983, days
Steelhead	Bonneville Dam	7.7-16.4 hrs	"	Fall 1983, nights
Mixed	Ice Harbor Dam	1-2.1 min/pool	Weaver 1962	1:10 fishway, 74 pools
Mixed	Ice Harbor Dam	1-2.3 min/pool	"	1:16 fishway, 74 pools
Chinook	McNary Dam	2.5-2.8 min/pl	U.S. Army Corps 1961	1956, 58 pools
Chinook	McNary Dam	3.3 min/pool	"	1957, 58 pools
Chinook	Bonneville Dam	2.8 min/pool	Collins et al. 1963	1:8 experimental fishway
Chinook	Bonneville Dam	2.3 min/pool	"	1:16 experimental fishway
Chinook	Rocky Reach Dam	3.0-4.5 days	Major & Paulik 1972	1964-65
Chinook	Bonneville Dam	63.0 hrs	Monan & Liscom 1971	Spring 1971
Chinook	Bonneville Dam	22-64.0 hrs	Monan & Liscom 1973	Spring 1972
Chinook	The Dalles Dam	6.0 hrs	"	Spring 1972

Table 1. Continued.

Species	Location	Migration rate	Source	Comments
Chinook	John Day Dam	2.0 hrs	Duncan et al. 1974	1972-73
Chinook	Lower Monumental Dam	0.73-0.82 hrs	Monan & Liscom 1974b	Spring, north fishway
Chinook	Lower Monumental Dam	2.3-3.5 hrs	"	Spring, south Fishway
Chinook	Bonneville Dam	8.5 hrs	Monan & Liscom 1975	Spring 1974
Chinook	Bonneville Dam	4.9 hrs	"	Summer 1974
Chinook	The Dalles Dam	4-7.0 hrs	Duncan et al. 1978	Fall 1974, 1975
Chinook	The Dalles Dam	3-4.0 hrs	"	Spring 1975
Chinook	Lower Granite Dam	4 hrs	Liscom & Monan 1976	1975
Chinook	Bonneville Dam	3.7 hrs	Monan & Liscom 1976	Summer 1975
Chinook	The Dalles Dam	5.5 hrs	"	Summer 1975
Chinook	Bonneville Dam	2.9 hrs	Johnson et al. 1979	1978
Chinook	John Day Dam	3.0 hrs	Johnson et al. 1982	Fall 1979-80
Chinook	Bonneville Dam	3.1-3.5 hrs	Ross 1983	Spring 1982, days
Chinook	Bonneville Dam	14-30.5 hrs	"	Spring 1982, nights
Chinook	Bonneville Dam	2.8-3.9 hrs	"	Summer 1982, days
Chinook	Bonneville Dam	6.2-12.8 hrs	"	Summer 1982, nights
Chinook	Bonneville Dam	2.8-4.7 hrs	"	Fall 1982, days
Chinook	Bonneville Dam	11.1-14.4 hrs	"	Fall 1982, nights
Chinook	Bonneville Dam	0.8-2.8 hrs	Turner et al. 1984	Spring 1983, days
Chinook	Bonneville Dam	5.3-13.6 hrs	"	Spring 1983, nights
Chinook	Bonneville Dam	2.4-3.3 hrs	"	Summer 1983, days
Chinook	Bonneville Dam	3.2-11.8 hrs	"	Summer 1983, nights
Chinook	McNary Dam	2.4 hrs	Shew et al. 1985	Spring chinook
Chinook	McNary Dam	3.9 hrs	"	Summer chinook
Chinook	Bonneville Dam	2.5-3.3 hrs	Shew et al. 1988	Day time, 1984
Chinook	Bonneville Dam	11-12 hrs	"	Night time, 1984

moved upstream within 20 to 30 m of the shore and within 1.5 m of the bottom in the slow water velocities.

Cool water temperatures in the summer and early fall can also influence the upstream migration of salmon and steelhead and lead to what appears as straying. Steelhead destined for Snake River tributaries upstream from the Clearwater River mouth, were found to enter the Clearwater River in August and early September when large discharges of cool water from Dworshak Dam created a temperature difference between the Snake and Clearwater rivers (Stabler et al. 1981). The fish eventually returned to the Snake River and continued their migration upstream. Steelhead migrating up the lower Columbia River have been observed making similar temporary detours into cool water tributaries (notably the Little White Salmon and Deschutes rivers).

A similar detour into cool water by chinook salmon was observed by Stabler et al. (1981) in the Clearwater River in 1976. Prior to construction of Dworshak Dam, the temperature of flows from the North Fork of the Clearwater River were similar to those in the mainstream. In late July and early August of 1976, however, water released from Dworshak Dam was 1 to 7°C cooler than the mainstream Clearwater River. Of the six radio tagged chinook salmon tracked through the Clearwater-North Fork confluence area, all six entered the North Fork at least once, and remained in the North Fork for periods ranging from 7 h to 10 d before resuming their migration upstream. Fish tracked prior to late July, when there was not a large variance in the temperature of the two rivers, did not enter the North Fork.

Additional information on the upstream migration ability of sockeye salmon has been obtained in other drainages and in test flumes. The swimming ability of sockeye salmon as they moved upstream was evaluated in a 1956-57 experiment by forcing them to swim at constant velocities and temperatures in flumes until exhausted (Paulik and DeLacy 1958). Sockeye salmon used in the tests were collected as the peak of the run passed five locations on the Columbia and Wenatchee rivers; Bonneville, McNary, Rock Island, Tumwater, and White River dams. Paulik and DeLacy reported that the swimming abilities of the sockeye salmon tended to decrease with the distance the fish had moved upstream from Bonneville Dam, and that fish exhausted during the daily trials died sooner than control fish that were not tested. In the Karluk River, Alaska, in 1945-46, Gard (1973) found that tagged sockeye salmon migrated at rates of 4.7-5.3 km/d in the spring and 3.2-3.4 km/d in the fall. Sockeye salmon were observed to migrate 9.5 to 39.7 km/d in the Columbia River in 1953-54 and 1962-63 (Major and Mighell 1966).

Flows in the rivers also influence the upstream migrations of salmon and steelhead, but the effect of the flow cannot be separated from that of the dam where the fish are counted. Davidson (1957) investigated the effects of floods on the Columbia River to chinook salmon movements by comparing counts at Bonneville Dam to changes in water levels. During 1939 and 1940, which had moderate spring runoffs (180-390 kcfs), the spring chinook salmon run was depicted by a smooth bell-shaped curve through the season. The spring runoffs were high in 1948 (400-1,000 kcfs) and 1949 (360-632

kcfs). During those years the spring chinook salmon counts dropped from 4,000 fish/d to less than 100 fish/d during the peak floods. Fish counts then increased as the flows subsided. Davidson suggested that high turbidities and velocity barriers inhibited the upstream movement. Similar effects were seen at Rock Island Dam (Davidson 1957). Rapid increases of flow tended to temporarily halt upstream movement of salmon at the dam, independent of the initial flow level, whereas a gradual increase in flows to 400 kcfs seemed to have little effect on upstream movement. When flows reached 500 kcfs movement was significantly reduced, and stopped all together at 600

kcfs. In both of these cases, we do not know if the migration would have been delayed if the dam had not been there.

There was no evidence that flows in the Columbia or Snake rivers have ever decreased to a point where upstream movement would be limited. In smaller tributaries, irrigation diversions have reduced flows to such low levels that fish could not migrate upstream. In the River Vefsna, Norway, Atlantic salmon would not move upstream until flows were above 70 kcfs (Jensen et al. 1986; Jensen et al. 1989).

Migration Past Dams

Passage conditions at dams can vary seasonally and annually. Aside from the physical structure itself, the main features restricting or enhancing passage of adult salmonids over a dam are the operational procedures and the amount, timing and distribution of water passed through the dam. The studies reviewed in this section deal specifically with the affects of power-peaking flows, spill patterns, and powerhouse discharge patterns on adult passage at lower Columbia and Snake River dams.

Successful passage of dams by adult salmon and steelhead migrating to the spawning grounds includes finding the entrances to the fishways amid the array of currents that are often present, moving into and up the fishways, and entering the forebay, and proceeding upstream without falling back over the dams via the spillways or through the intakes to the turbines. Passage is most efficient when:

(1) there are suitable attraction flows to lead fish to the fishway entrances, (2) the entrances to fishways can be found and entered without difficulty, (3) fish migrate rapidly through the fishways, and (4) the fish are not likely to fallback over the dam. However, adult passage at dams is not always successfully accomplished. Flows at the dams, turbidity of the water, the amount of water spilled, the pattern of spill, and the discharge through the turbines can complicate and reduce the efficiency of adult fish passage at dams, as demonstrated by the delays and mortalities of salmon and steelhead observed at the Columbia and Snake River dams.

An extreme example of the loss than can occur at a dam is that which occurred in 1968 at John Day Dam (under construction at that time), when most of the flow was spilled, supersaturation of dissolved gases was high, and there was an estimated loss of 20,000 spring and

summer chinook salmon. An additional 32% of fish migrating between John Day and McNary dams were also estimated to have been lost (Haas et al. 1969; Haas et al. 1976). Failure to find the fishway entrances rapidly was reported as a partial cause of the losses.

Less severe delays of adult salmonids have been reported for Snake River dams, and the delays generally increased with river flows. Spring chinook salmon tracked at Lower Monumental Dam during a 1973 study investigating the effect of spillway deflectors on adult passage were delayed an average 42.0 h during low river flows (39.2 kcfs), and 84.3 h during high river flows (76.9 kcfs) (Monan and Liscom 1974a; Monan et al. 1979a).

In 1976 and 1977, Haynes and Gray (1980) found the delay of chinook salmon with transmitters averaged 216 and 90 h at Little Goose Dam, and 50 and 58 h at Lower Granite Dam for the two years, respectively. Flows were unusually low in 1977.

In a 1981 study (Turner et al. 1983), spring chinook salmon with radio transmitters were delayed an average of 37.4 h at Little Goose Dam. At Lower Granite dam, delays averaged 31.7 h during low flows (spill <25 kcfs), and 176.3 h during high flows (spill >25 kcfs). In 1982, a year with above average flows, median delays of radio-tracked spring chinook salmon were 118.6 h at Ice Harbor Dam, and 44.8 h at Lower Monumental Dam (Turner et al. 1984).

Delays of chinook salmon have also been measured at Columbia River dams through the use of tagged fish. At

Bonneville Dam adult migrants were delayed 2 to 3 days in 1948 (Schoning and Johnson 1956), 1 to 4 days during 1973-76 (Gibson et al. 1979), 2 days in 1977 (Liscom et al. 1978), 2 days in 1978 (Johnson et al. 1979), 1 to 1.5 days in 1983 (Turner et al. 1984), and 2 days in 1984 (Shew et al. 1985). Similar delays were reported for chinook salmon at The Dalles and John Day dams (Monan and Liscom 1973; Liscom et al. 1978; Gibson et al. 1979; Johnson et al. 1982; Liscom and Stuehrenberg 1983; Shew et al. 1985; Shew et al. 1988). Chinook salmon experienced a 1 day delay at McNary Dam in 1982 and 1985 (Liscom and Stuehrenberg 1983; Shew et al. 1985).

Estimates of mortalities of adult salmon and steelhead attempting to pass dams are difficult to make and little has been reported. Estimates of mortalities of adult salmon at Columbia River dams have ranged from 4% to 29% (French and Wahle 1966; Gibson et al. 1979; Merrell et al. 1971; Weiss 1970; Young et al. 1978). In general, adult passage is more difficult (increased delays and mortalities) during the high spring runoff flows than during lower flows (Merrell et al. 1971; Monan and Liscom 1971; Liscom et al. 1979; Gibson et al. 1979; Bjornn and Rubin 1992).

Entry Into Fishways

The success of adult salmon and steelhead passage at Columbia and Snake River dams is dependent on the migrants locating the fishway entrances and moving into and up the fishways without undue delay (Clay 1961). Factors that influence the efficiency of fish entry into the fishways include the flow conditions in the tailrace and near the entrances to the fishways,

and the physical characteristics of the entrance (size, shape, location, and flows).

Tailrace flow patterns.-The tailrace is defined in this report as the area downstream from the dam that is influenced by discharges from the dam, the majority of which comes from the spillway and/or powerhouse. The tailrace may extend downstream several hundred meters during periods of high flows, and to a lesser distance during low flows. The amount of water passing a dam and the proportion passing over a spillway versus through the powerhouse create the flow patterns in the tailrace, and those patterns influence how easily fish find the entrances to the fishways.

Typically, most of the Snake River flow is passed through the powerhouse of the dams, with periods of spill occurring mainly during the spring runoff season. The distribution of flows from the dams influences which fishway, and which fishway entrances will be used by the upstream migrants to pass the dam. The influence of powerhouse versus spillway discharges in shifting the use of fishway entrances by salmon and steelhead at Snake River dams was illustrated by Junge and Carnegie (1973). At Ice Harbor Dam, when all but 1 kcfs of the discharge during the July test period (flow averaged about 76 kcfs) was through the powerhouse, an average of 650 fish/d were counted through the powerhouse fishway and only minimal numbers used the north/spillway fishway (about 50 fish/d). When 20% (about 15 kcfs) of the powerhouse flow was shifted to the spillway, passage through the powerhouse fishway dropped slightly to 625 fish/d, but passage in the spillway fishway increased

to about 250 fish/d. At Lower Monumental Dam, the shifts in fishway use were larger. When flows through the powerhouse were dropped from 68 to 49 kcfs (28% reduction) and spill was increased from 0 to about 14 kcfs, passage through the powerhouse fishway decreased from about 550 to less than 350 fish/d (40% reduction), but passage of salmonids through the spillway fishway increased from less than 100 to over 900 fish/d. Junge and Carnegie (1973) concluded that passage conditions for upstream migrants were less than optimum when water was discharged only from the powerhouse. When a small amount of water was spilled to attract fish to the spillway fishway, the overall rate of fish passage over the dam increased. Salmon and steelhead approaching the dam when all the discharge was from the powerhouse were apparently having difficulty locating the fishway entrances among the turbulent discharges from the powerhouse.

At Little Goose Dam in the spring of 1981, all of the river flow (up to nearly 130 kcfs) was passed through the powerhouse, except during the last four days of the 54-day study period. During the non-spill period the majority of the fish entered the fishway through the powerhouse entrances. But, during the period with spill (up to 60 kcfs), entry to the fishway shifted to the spillway entrances (a confirmation of the observations by Junge and Carnegie in 1972 that fish may have difficulty locating the powerhouse entrances to the fishway). At Lower Granite Dam in 1981, spill occurred on 33 of the 54 day study. During the period of non-spill the discharge from the powerhouse ranged from 50 to 85 kcfs and again the majority of the fish used the powerhouse entrances to gain access to

the fishway. On days that spill occurred most of the fish used the entrances adjacent to the spillway until high spills (>50-60 kcfs) blocked access to those entrances.

During the 1982 spring study conducted at Ice Harbor and Lower Monumental dams flows were higher than in 1981. At Ice Harbor Dam, where spill ranged from 30 to 60 kcfs during most of the 59-day study period and powerhouse discharge ranged from 50 to 90 kcfs, about four-fifths of the adult chinook salmon passed over the dam via the south shore (powerhouse) fishway and one-fifth via the north shore fishway adjacent to the spillway. At Lower Monumental Dam in 1982, discharges from the powerhouse ranged from 20 to 100 kcfs and spill ranged from 40 to 100 kcfs during the spring study period (Turner et al. 1984). About two-thirds of the fish passed over Lower Monumental Dam via the north shore (powerhouse) fishway and one-third over the south shore fishway adjacent to the spillway.

Powerhouse discharges- Entrances adult salmon and steelhead use to enter fishways and the ease of entry can be affected by the amount and distribution of water discharged from powerhouses. The shift in entrance use at dams under various powerhouse flow conditions was monitored in 1981 and 1982 at the four lower Snake River dams by placing electronic counting tunnels in each of the fishway entrances (Turner et al. 1983; 1984).

At Little Goose and Lower Granite dams the powerhouses are adjacent to the south shore and the spillway is north of the powerhouse, at about mid-channel. Each

dam contains a single fishway with a ladder on the south shore. There are three entrances to the fishway north of the spillway (NSE-1, NSE-2, NSE-3) and the powerhouse has a total of 15 entrances, three at the north end (NPE-1, NPE-2, and NPE-3), ten submerged orifices along the face (four were in use during the study), and two at the south end (SSE-1, SSE-2). The south shore entrances lead directly to the ladder, while the remaining entrances lead into a collection channel that runs under the spillway and along the powerhouse. Ice Harbor Dam is similar to Lower Granite Dam, with the powerhouse adjacent to the south shore and the spillway north of the powerhouse, while at Lower Monumental dam the positions are reversed. Ice Harbor and Lower Monumental dams have two fishways, one along each shore. The fishway entrances at these two dams are similar to those described for Little Goose and Lower Granite dams, except that Ice Harbor Dam has 12 submerged orifices at the powerhouse (seven were used).

At Little Goose Dam in 1981, when all of the discharge (up to nearly 140 kcfs) was through the powerhouse, fish entry rates were highest at the south powerhouse entrances, followed by the north powerhouse entrances, the north spillway entrances, and then the floating orifices along the face of the powerhouse. During lower powerhouse discharge (<90 kcfs) fish entered all of the powerhouse entrances, but when discharges exceeded 90 kcfs, the middle floating orifice entrances were little used.

At Lower Granite Dam in 1981, turbine number 3 was not in service and there was spill on 33 d of the 54-d study period.

During the period of no spill, discharges from the powerhouse ranged from about 50 to 85 kcfs, and the largest number of fish entered the fishway at the south powerhouse entrances, followed by north spillway, and then the north powerhouse entrances. A small number of fish entered through the powerhouse floating orifice entrances. Although no water was discharged from turbine 3 outlets, the gap in discharge did not result in increased numbers of fish entering the fishway through the floating orifices adjacent to that unit. The chinook salmon with radio transmitters approached the dams along the shore lines and tended to concentrate downstream from the powerhouse, especially during zero to low spills (0 to 25 kcfs). When there was spill, more of the fish approached the dam along the north side of the river and entered the fishway through the entrances at the north end of the spillway, until very high spills (>50-60 kcfs) blocked access to those entrances.

At Ice Harbor Dam in 1982, where spill ranged from 30 to 60 kcfs during most of the study period (12 April to 9 June) and powerhouse discharge ranged from 50 to 90 kcfs, the highest entry rates of fish (mostly chinook salmon) into the fishways were at the entrances at the north end of the powerhouse (net entry (26.3% of total) (Turner et al. 1984). Fewer fish entered the other entrances to the powerhouse fishway compared to those at the north end, but the fallout rate was low or nil. On the few days when powerhouse discharges were relatively low (< 59.9 kcfs) and spill increased, the fish tended to congregate at the south end of the powerhouse, and more fish used the south shore entrances (40% of net passage).

At Lower Monumental Dam in 1982, discharges from the powerhouse ranged from 20 to 100 kcfs and spill ranged from 40 to 100 kcfs during the study period (Turner et al. 1984). The chinook salmon approached the dam along the north shore, and of the fish entering the north shore (powerhouse) fishway, the largest number entered the entrance at the north end of the powerhouse (48.3% of net entries). Fish also entered the fishway via the powerhouse floating orifice gates with few fallouts. More fish fell out of the entrances at the south end of the powerhouse than entered.

Shifts in entrance use with shifts in powerhouse flow have also been observed at Columbia River dams. For example, the entrances used by salmon and steelhead to enter the fishways at John Day Dam was influenced by turbine discharge during a 1972-73 study (Duncan et al. 1974). With full powerhouse discharges, the fish tended to move along the downstream edge of the powerhouse outflow, and to use the outer entrances to the south shore fishway. At lower powerhouse discharges, fish entered the fishway according to the number and location of turbines being used. For example, when units 1 through 4 were shut down the number of fish entering orifices 1 through 4 decreased, but entry via orifice 5 increased. Use of the south-shore fishway entrance was highest when turbine number 1 (the closest turbine) had a discharge of 10 kcfs, but decreased by 7% to 65% when operated at 15 kcfs, and by 38% to 73% when the turbine was shut down. Duncan et al. (1974) concluded that the upwelling boil from turbine 1 at the 15 kcfs discharge level blocked access to the south entrance, but attraction to the entrance was

completely eliminated when turbine 1 was shut down. To reduce blockage to the fishway at high turbine discharge, Duncan et al. (1974) recommended that the south entrance be extended downstream away from the turbine boil, or to close off the south entrance and use the first submerged orifice gate as the primary entrance to the fishway.

In contrast to the results seen at John Day Dam, passage over the Bradford Island fishway at Bonneville Dam was 8% higher when turbine number 1 was shut down than when it was operating (11 kcfs maximum flow) (Junge 1969). The difference between the entry behavior seen at the two dams was most likely related to differences in the configuration of the two dams and the tailraces. Similar patterns of fish approach to the powerhouses and use of entrances as reported for John Day Dam (Duncan et al. 1974) were found during 1974-75 studies conducted at The Dalles Dam (Arndt et al. 1976; Duncan et al. 1978).

Cramer et al. (1959) found that passage over McNary Dam was not affected by closure of the south entrance to the powerhouse fishway during studies conducted in 1955, 1957, and 1958. They concluded that closure of one entrance increased the attractive flows at the open entrances.

Power peaking.- Power peaking involves passing more water through the powerhouse when the demand for power is high (weekdays), and storing water behind the dams when power demands are low (at night and on weekends). The result of peaking operations can range from total cessations of river flows (zero flows) during water storage, to high flows during

peak power generation, and sudden changes between the two conditions. Concerns about how these flow manipulations affect the upstream migrations of salmon and steelhead in the Columbia and Snake rivers prompted the investigation of salmonid behavior under peaking conditions. The effects of zero-flow conditions on salmonid behavior will be covered later in the section on migrations through reservoirs.

A major concern of those investigating the effects of peaking flows on upstream migration of salmonids was the effect that the altered powerhouse discharges and sudden discharge changes would have on passage conditions at dams. For example, adult passage over Ice Harbor and Lower Monumental dams increased significantly during a 1972 study when flows were shifted to the spillways to simulate a 40% flow reduction through the powerhouses (U.S. Army Corps of Engineers 1979c). The reduction of powerhouse discharge from 60 to 36 kcfs at Lower Monumental Dam resulted in fewer fish using the north shore (powerhouse) fishway, and more fish using the spillway fishway, but a net doubling of the number of fish passing over the dam per day.

During peaking operations at The Dalles Dam in 1969 and 1970, spring and summer salmonid passage was 13 to 50% higher on the weekends, when powerhouse discharges were reduced, than on weekdays. The spring salmonid passage at Priest Rapids Dam ranged from 14 to 83% higher on weekends (powerhouse discharge <100 kcfs) than on weekdays (powerhouse discharge from 115 to 125 kcfs) from 1966 to 1970 (Junge 1971). Junge suggested that the

increased turbulence below the dam during the high discharge obstructed entry to the collection system.

Reduced powerhouse discharge also improved the passage of fall chinook salmon with radio transmitters (45 fish) at Bonneville Dam during a 1973 study designed to investigate the effects of peaking on passage conditions (Monan and Liscom 1974a). Discharge from nine turbines were reduced by 1/2 to 2/3 of normal, starting from the end turbines and working inward, resulting in increased passage of the fish with transmitters from 1.3 fish/d at the normal turbine discharge (averaged 108 kcfs) to 1.9 fish/d at reduced levels (averaged 88.6 kcfs).

Peaking operations may also contribute to the mortalities occurring at dams. During a 1973 study of mortality and delay of summer and fall chinook salmon in the lower Columbia River, Young et al. (1974) suggested that mortalities were higher on weekdays than on weekends because of peaking flows. In a similar study conducted in 1975, tagged summer chinook salmon experienced higher mortality (21.3%) at John Day Dam with full loads of 20-23 kcfs at each of the three turbines nearest the south fishway entrance and no spill, than with reduced turbine discharges of 12-15 kcfs at each of three turbines and 72 kcfs spill (17.4% of total flow), although the difference was not significant (Young et al. 1977).

Secondary to the amount of flow released, the rate of change of flows released from dams and fish passage has been a matter of concern, but the relationship is not well understood. During a 1970 study, Wagner (1971) reported that

flows released from Ice Harbor Dam could fluctuate from 7.7 to 44.1 kcfs within a day. He found that on days when flows caused the tailwater level to fluctuate by 1.1 ft or less the passage of steelhead over Ice Harbor Dam was relatively constant through the day. During days when tailwater fluctuations were greater than 1.1 ft steelhead passage decreased, with numbers peaking at certain times of the day, suggesting the fish were delayed in crossing the dam under certain conditions. In the Clearwater River, steelhead radio-tracked during a 1980 study showed no unusual behavior when discharge changes of 1, 2, or 3 ft/h from Dworshak Dam were tested (Bjornn and Ringe 1982). When investigating the effect of peaking flows on passage at the The Dalles Dam collection system, Arndt et al. (1976) found that entry to the fishways was not altered by rates of change of turbine discharge of 1 kcfs/3 minutes and 1 kcfs/24 seconds.

Spillway discharge patterns.-Water is spilled through the spillways at dams when the river flow exceeds the capacity of the powerhouse or the power demand, and when there are special requirements for spill such as downstream migrant passage. When water is spilled the flow patterns downstream from the dams are changed. Fish are often attracted to the spillway discharges, which may be beneficial if the fish are led to fishway entrances, or detrimental if they are not. Spilling of water at the dams is normally associated with high flows and sometimes high turbidities; the three factors combined can cause reduced passage efficiency. In this section we will review studies that were designed specifically to evaluate the effect of spill volume and patterns on adult passage at dams.

The effect of spill pattern on passage of adult salmon was demonstrated at Ice Harbor Dam. "Losses" (discrepancies in fish counts) of spring chinook salmon between McNary, Priest Rapids and Ice Harbor dams from 1962 to 1966 increased with increased river flows and were associated with poor passage conditions at Ice Harbor Dam (Junge 1966a). From 1963 to 1966 the standard practice at Ice Harbor Dam was to use a uniform spill pattern, with gates 1 and 10 closed or only slightly opened, and gates 2 to 9 opened an equally large amount. Spring chinook salmon losses during this period were high, ranging from 33.7 to 41.2%. In 1967 a crowned spill pattern was used for flows between 40 and 80 kcfs, and losses decreased to 26.4% (Junge 1967). From observations made during the 1967 season, Junge recommended a spill pattern for Ice Harbor Dam that used split spills below 30 kcfs, a transition pattern from 30 to 40 kcfs, and a crowned pattern at spills larger than 40 kcfs. As river flows continue to increase the spill pattern gradually became more uniform to accommodate the flows. In 1968, the first year that the recommended spill schedule was used, spring chinook salmon losses reached their lowest level at 17% (Junge 1969). From 1968 to 1975 the "losses" of spring chinook salmon between McNary-Priest Rapids-Ice Harbor dams dropped to an average of 13% (Junge and Carnegie 1976a). These losses were determined to be independent of river flow and were attributed to poor passage conditions at Priest Rapids Dam. The addition of three new turbines to Ice Harbor in 1976 required adjustment to the spill schedule, especially for the higher flows (U.S. Army Corps of Engineers 1979a).

The effect that high flows and spill can have on fish passage at the Snake River dams was further defined in 1981 and 1982 studies. During 1981, 36 chinook salmon outfitted with radio transmitters were released at Lower Monumental Dam, and 8 were released upstream from Little Goose Dam, and tracked until they crossed Lower Granite Dam (Turner et al. 1983). There were only four days of spill at Little Goose Dam in 1981 during the 20 April to 19 June period of study and thus most of the fish passed the dam under no-spill conditions and were delayed only 1 to 1.5 d. At Lower Granite Dam in 1981, spill occurred on 33 of the 54 d study period, and fish were delayed in passing the dam up to 7.5 d when spill exceeded 40 kcfs. During periods of low spill, and low river flows, the delay was only 1 day. In 1982, the snowmelt runoff was larger than average and there was spill throughout the study period at Ice Harbor and Lower Monumental dams (Turner et al. 1984). Thirty-one chinook salmon were outfitted with radio transmitters and released downstream from Ice Harbor Dam, and four fish were released in the forebay, and all were tracked until they passed over Lower Monumental Dam. Eight chinook salmon with transmitters installed at Bonneville Dam during a separate study were also monitored. The delay in passing Lower Monumental Dam during this period was an estimated 2 to 2.5 d.

Spill patterns have been developed for all the Columbia and Snake River dams based on information available. Because of structural differences at each of the Snake River dams, the spill patterns are not the same. Little Goose, Lower Monumental, and Lower Granite dams each contain eight spillbays and a more

channelized tailrace, which led Junge and Carnegie (1972; 1976a) to recommend a more uniform spill pattern at those dams versus the crowned pattern at Ice Harbor Dam.

In a report to the U.S. Army Corps of Engineers, Junge and Carnegie (1972) discussed in depth the guidelines that should be followed while developing spill patterns for Columbia and Snake River dams. They explained that the amount and location of spill required to produce adequate passage conditions will vary with river flow and powerhouse discharge levels. In most cases, fishway entrances flank the spillway. For fish to successfully locate the entrances, fishway flows should be uninterrupted and directed downstream. High turbulent flows near fishways entrances can mask the attraction flows, while misplaced flows can attract fish away from the entrances and increase delays in entering the fishways. The optimal spillway flow will set up a velocity barrier angling toward the fishway entrances to guide fish to the fishway openings. During high river flows, Junge and Carnegie recommended that a crowned spill pattern be used whereby spill is highest through the central spillbays and decreases outwards to the end bays, forming a V-shaped flow pattern in the tailrace. When relatively little spill occurs, a split spill pattern was recommended where the flow is concentrated in the end bays to enhance attraction toward the fishway entrances.

Spill conditions described by Junge and Carnegie (1972) that should be avoided include differences of gates openings of four feet or more in adjacent spillbays. This situation creates a slack water area adjacent to a high velocity jet.

Fish crossing from the slack water area into the high velocity jet will most likely be killed from the high shear force. High spills in the end bays can create the greatest problems by producing high velocities, turbulence, and vortexing that will completely block access to the fishway entrances. High spills can also create currents that will misguide fish away from the entrances. When high spills combine with turbine discharge standing waves can form which will block access to collection system entrances. When spill through the end bays is too low relative to the central bays an eddy can form along the shoreline which can eliminate or even reverse flow direction near the fishway entrance.

Spill patterns have been developed following the guidelines described above and used successfully at lower Columbia River dams. The major difference between Columbia and Snake River dams is the size of the spillway. With the larger spillways at Columbia River dams a modified crowned spill pattern is used where flows through the end three or four bays is gradually reduced, but are kept generally uniform through the central spillbays (Junge 1969; Junge and Carnegie 1976a).

The addition of spillway deflectors to dams in the 1970's required adjustments to the spill schedules to maintain adequate passage conditions. Spillway deflectors are a lip added to the spillbay that deflects the water away from the dam on the surface of the tailrace to reduce gas supersaturation. Water flowing through the spillbays with deflectors have a higher surface velocity than that going through spillbays without deflectors, and this led to questionable passage conditions below

certain dams (Junge and Carnegie 1976b). During operational studies conducted at Little Goose Dam in 1976, the high velocity flows from spillbays 2 through 7, which had deflectors, were contained and passage improved, by increasing the amount of spill passing through the end bays, 1 and 8 (U.S. Army Corps of Engineers 1979a). Similar methods for containing the deflector flows have been used at the other Columbia and Snake River dams. Spillway deflectors had no effect on salmonid movements below dams (Monan et al. 1979b; Monan and Liscom 1976).

Fishway entrances.-The best location for a fishway entrance is thought to be the farthest upstream point reached by the migrating fish (Clay 1961). Since salmonids tend to move upstream along the shore, fishway entrances have been placed at the junction of the dam and the river bank. This principle is illustrated at The Dalles Dam where the powerhouse tailrace forms a channel running along the south shore. Fish moving upstream along the Oregon shore are attracted by the powerhouse flow into the tailrace area and are eventually guided to the east fishway entrance at the upstream end of the channel. Use of the east fishway entrance at The Dalles Dam during evaluation studies of the collection system (1974-75) was found to be consistently high, especially during the summer and fall when most of the river flow was passed through the powerhouse (Duncan et al. 1975; 1978). The large powerhouses used at the Columbia and Snake river dams were expected to draw fish to the area of the turbine discharge, and thus prompted the development of the fish collection systems along the face of the powerhouse.

Characteristics of fishway entrances relative to use by upstream migrating adult salmon and steelhead have been studied primarily at Bonneville Dam and at the Bonneville Fisheries-Engineering Research Laboratory (U.S. Army Corps of Engineers 1953, 1956a, 1956b, 1960; Thompson et al. 1967; Weaver et al. 1976). At Bonneville Dam, orifices were found to be more effective than overflow weirs as entrances to the powerhouse fishway, especially during variable (peaking) flows. In 1954, passage over Bonneville Dam was 15.6% higher with 6 ft deep orifices than with 10, 14, and 30 ft deep orifices. At the Bonneville Dam powerhouse in 1955 and 1956, the use of ten submerged orifices (60 cfs each) produced higher passage rates than with sixteen or six orifices. Passage was also found to be higher when using larger orifices (7.5 x 2 ft, 90 cfs) than either small (5.58 x 1.33 ft, 45 cfs) or intermediate sized (6.67 x 1.5 ft, 60 cfs) orifices, with an 18 inch head versus a 12 inch head at the orifices, vertically versus horizontally orientated orifices, and lighted orifices over a dark, but that use of the dark orifice increased with hydraulic head. At The Dalles Dam, optimal entry conditions with overflow weirs occurred when using weir depths of 7 to 9 ft and heads of 1 ft or greater (Junge and Carnegie 1970; Duncan et al. 1978).

Both the quantity and velocity of water exiting the fishways are important in attracting fish to the entrances once they have moved to the vicinity of the entrances. In his book on fishway design, Clay (1961) recommended that entrance velocities be at least 4 fps but less than 8 fps to create optimal entry conditions. These values were based on the behavior

and swimming ability of salmon and steelhead. During a 1957 study at the Bonneville Fisheries-Engineering Research Laboratory, steelhead, and coho and chinook salmon had a higher preference for the higher velocities when exposed to various combinations of flows of 2, 3, 4, 6, and 8 fps, except that no difference was found between 6 and 8 fps (Weaver 1963). Bell (1984) reported that the sustained swimming speeds (which can be maintained for a few minutes) for steelhead, coho and chinook salmon were about 10 fps. An example of the importance of flow quantity was illustrated by Junge and Carnegie (1970), when fish passage through a fishway at The Dalles Dam dropped by half when flows in the fishway were halved.

The addition of side entrances (facing into the spill basin) to the powerhouse fishways at Lower Monumental (1972) and McNary dams (1974) significantly increased salmonid passage over these dams during periods of low spill. Passage over Lower Monumental Dam averaged 60% higher through the powerhouse fishway when the side entrance and one downstream entrance was used versus both downstream facing entrances (U.S. Army Corps of Engineers 1979b). Junge and Carnegie (1973) recommended the use of the side entrances at Lower Monumental and Little Goose dams during periods of no spill.

The use of all entrances at Snake River dams was evaluated in 1981 and 1982 by Turner et al. (1983; 1984). At both Little Goose and Lower Granite dams in 1981, the fishway entrance data was confounded by high rates of fallout (fish exiting the fishway via an entrance) at

several of the entrances. At Little Goose Dam, large numbers of fish exited the fishway via the south entrance and the two north powerhouse entrances (NPE 1 and 2). Exit rates for Little Goose Dam (expressed as a percentage of the entry rate) were 12.5% for NSE, 65.3% at NPE-1, 99.3% at NPE-2, 15.5% at the four orifice gates combined, and 62.6% for SSE. At Lower Granite Dam, during periods of no spill, the largest numbers of fish exited the fishway via the north and south entrances. During periods of spill, most of the fish entered via the north entrances and similar numbers exited the north, north powerhouse, and south entrances. The species of fish entering and exiting the entrances was not determined.

Migration Through Fishways

Fishways at the Columbia and Snake River dams include the entrances, collection channels, ladder sections, and exits. Most fishways at Snake River dams have a 1:10 slope, except for the 1:16 sloped powerhouse fishway used at Ice Harbor Dam (Turner et al. 1983; 1984). In studies conducted at the Fisheries Engineering Research Laboratory, steelhead and sockeye salmon successfully passed through an experimental 1:8 sloped fishway (Collins and Elling 1958; Connor et al. 1964), however, chinook salmon were stressed by passage through the 1:8 fishway until baffles were added that induced the fish to rest during ascents (Collins et al. 1963). Chinook salmon generally were attracted to the highest velocity flows (Weaver 1968), but adult migrants (especially coho

and sockeye salmon) may tire during extended climbs at flows of 4 fps or higher unless rest areas are provided (Delacy et al. 1956; Paulik et al. 1957). Flows as low as 1 fps work well for passing steelhead, chinook, and sockeye salmon through transportation channels, but require auxiliary water to attract fish to the channels (Gauley 1966). Fish will use the fishway with the best attraction flows (see Entry Into Fishways).

Flows, water velocities, and fishway design have a major effect on the successful passage by salmonids. Bell (1984) reported that adult salmon and steelhead are able to swim at cruising speed (about 1.2 m/s) for hours, and that faster speeds (up to 7 m/s) can only be maintained for minutes or seconds. The endurance of coho and sockeye salmon was tested in 1956 and 1957 by forcing them to swim at various speeds in either a circular rotating or straight flume (Delacy et al. 1956; Paulik et al. 1957; Paulik and Delacy 1957, 1958). Most sockeye salmon tested could not maintain position in velocities of 1.3 m/s (4.5 ft/s) longer than 10 minutes, although some lasted up to 20 minutes. Burst speed swimming by sockeye salmon of up to 3.35 m/s (10 to 11 ft/s) was maintained for only a few seconds (Delacy et al. 1956). At 2.0 m/s (6.6 ft/s) the endurance of sockeye salmon from the lower Columbia River ranged from 153.7 to 196.4 seconds, and at 2.9 m/s (9.4 ft/s) it ranged from 59.2 to 64.9 seconds (Paulik and Delacy 1958). Coho salmon tested in a rotating flume at the University of Washington could maintain their position against a flow velocity of 1.1 m/s (3.2-3.6 ft/s) for an average of 505 seconds (range = 185-1,032 seconds) (Paulik et al. 1957). Delacy et al. (1956) suggested that

velocities over weirs and through orifices could not be more than 3.0 m/s (10 ft/s) and should not be over about 2.4 m/s, and sufficient low velocity areas should be available within the fishway to allow salmonids to rest during the ascents. For extended lengths of 1,000 ft or longer, flows should not be higher than 1.2 m/s. Gauley (1966) reported that chinook salmon, steelhead, and sockeye salmon will readily pass through transportation channels in flows as low as 0.3 m/s.

Ice Harbor and Lower Monumental dams each have two fishways, one along the north shore and the other along the south shore. Little Goose and Lower Granite dams have a single fishway along the south shore. The north shore entrance at the latter two dams connects to the fishway via a lighted tunnel that passes under the spillways. All the fishways have a slope of 1:10, except the powerhouse fishway at Ice Harbor which has a slope of 1:16 (Turner et al. 1984). Ice Harbor was the first dam constructed on the lower Snake River (1961), and the first dam to have a fishway with a 1:10 slope. Previous to this Columbia River dams had been constructed mainly with 1:16 slope (16 ft long pools with a 1 ft rise between pools) fishways. The advantage of the steeper, and narrower fishway is the reduced construction cost.

To determine if adult salmonids would pass through 1:10 slope fishways as well as in 1:16 fishways, a study was conducted at the Fisheries Engineering Research Laboratory during 1960 (Thompson and Gauley 1965). During this study chinook salmon, sockeye salmon, and steelhead were timed while ascending a six-pool full scale model of the 1:10

fishway. Thompson and Gauley reported passage times through the model were about 1.1 minutes/pool for steelhead, 1.3 minutes/pool for sockeye salmon, and 2.2 minutes/pool (and 1.5 minutes/pool through the half-width fishway) for chinook salmon, rates that were similar to passage rates through a 1:16 fishway. In 1961, the first year of operation of the fishways at Ice Harbor Dam, the two fishways were divided down the middle and the fish passing up one side were timed through a 74-pool section. Weaver (1962) found that passage times ranged from 67 to 152 minutes through the one side of the 1:10 fishway, and from 80 to 168 minutes through the 1:16 fishway.

These results were not unexpected because salmon and steelhead had moved up through 1:8 slope fishways at the Fisheries Engineering Research Laboratory with little difficulty (Gauley 1960; Collins et al. 1962; Collins et al. 1963). In 1956 studies, the passage rates of groups of 20 steelhead or chinook salmon through a six-pool, 1:16 slope fishway (16 ft long pools with a 1 ft rise between pools) were compared to three 1:8 fishway designs; six, 8 ft long pools with a 1 ft rise between pools, four 12 ft pools with a 1.5 ft rise, and three 16 ft pools with a 2 ft rise (Gauley 1960). Gauley (1960) found that steelhead traveled faster through the 1:8 fishway with the 1 ft rise (10.21 minutes) than through the 1:16 fishway (15.42 minutes), while chinook salmon travelled slower through the 1:8 fishway with the 1 ft rise (14 minutes) than through the 1:16 fishway (8.32 minutes). There were no differences in the other comparisons of fish passage through the 1:16 and 1:8 fishways, although there was a trend for increased

travel times with increased rise between pools in the 1:8 fishways. When the experiments were repeated in 1957, the passage of individuals and groups of steelhead, chinook and sockeye salmon was either faster or not significantly different through the 1:8 fishway (1 ft rise) than through the 1:16 fishway (Gauley and Thompson 1962). Passage through the 1:8 fishway with a 1 ft rise between pools was slower for chinook salmon (12.3 vs 18.5 minutes) than through the 1:16 fishway.

To determine the effect of extended ascents in 1:8 and 1:16 fishways, the endless fishway was developed and used in 1958 (Collins and Elling 1958). The endless fishway consisted of an oval-shaped 16 pool fishway which simulated a longer fishway by circulating fish from the highest (last) pool to the lowest (first) pool by means of a movable lock. During the 1958 studies spring chinook and sockeye salmon were timed through 6.5 circuits (104 ft rise) of both the 1:8 and 1:16 endless fishways. Collins and Elling (1958) reported there was no difference in the passage times of fish between the two fishways. During a similar study in 1959, the passage rate of 13 chinook salmon through the 1:8 fishway was significantly higher (44.1 minutes/cycle) than through the 1:16 fishway (36.4 minutes/cycle) (Collins et al. 1963). When fish were not allowed to rest in the turn pools of the 1:8 fishway, travel times increased, and the chinook salmon especially, were found to be stressed (increased blood lactate levels). After the installation of baffles reduced the turbulence in the pools, the chinook salmon were able to rest and no difference was found in the blood lactate levels of fish from the 1:8 and 1:16

fishways (Collins et al. 1963). Extended climbs of 1,000 ft or more were also completed by several steelhead, and chinook and sockeye salmon in the 1:8 and 1:16 fishways with no observable effects on the fish (Collins et al. 1962).

Columbia and Snake River fishways use overflow weir designs in combination with submerged orifices. The Ice Harbor Dam fishway uses pools 16 ft wide, 10 ft long, with a 1-ft rise between pools (Thompson and Gauley 1965). The weir between pools has 6-ft overflow sections on the outer thirds and an 8-ft non-overflow section in the central portion. The central non-overflow section of the weir is bordered by two 18-inch baffles facing upstream that create a low velocity pocket where fish can rest. There are two submerged orifices, 18 inches square, at either end of the weir. During tests of the weir design in 1960 at the Fisheries Engineering Research laboratory, three weir crest designs were tested; The Dalles-type or sloped crest, the McNary-type or rounded crest, and the plane surface ogee crest, of which the McNary-type crest produced the smoothest flows and the lowest passage times (Thompson and Gauley 1965). In the lab study it was observed that in the spring, chinook salmon preferred to use the orifices to pass up the ladder, but in the summer and fall more fish passed over the weir. Steelhead passing in the summer and fall preferred the orifices, but sockeye salmon consistently preferred to pass over the weirs. Velocities were about 1 fps at the surface over the weirs and about 8 fps through the orifices with 1 ft of head.

The earlier constructed dams used a weir design such as at Bonneville Dam;

the pools are 40 ft wide, 16 ft long, with a 1 ft rise and 6 ft deep. Water flowed over the entire width of the weir and through one submerged orifice placed on alternate sides on successive weirs (Holmes and Morton 1939). During 1969 and 1970 a new fishway was designed at the Fisheries Engineering Research Laboratory which passed water through a vertical slot rather than over a weir or through an orifice (Monk et al. 1989). The vertical slot allows passage throughout the water column, and is effective without adjustments during fluctuating water levels. Sections of the vertical slot fishway were installed and they functioned successfully at John Day Dam (1970 and 1973) and at Bonneville Dam (1974) (Monk et al. 1989; Stuehrenberg et al. 1979; Weaver et al, 1976).

Passage through the fishways occurs mainly during daylight hours, but a percentage of the fish will use the fishways at night. In 1973-74, Calvin (1975) found a positive relationship between night time counts at lower Columbia River dams and the counts from the previous day, which he used to develop a method for estimating night time passage at dams. For this study night counts were made weekly during the peak of each of the runs of spring, summer and fall chinook salmon, coho salmon, sockeye salmon, steelhead and American shad, at the north and south counting stations at Bonneville, The Dalles, and John Day dams. Calvin found that the ratio of night/day counts varied by dam, counting station, and species. For example, the ratio for spring chinook salmon was 0.0583 for the north shore, and 0.0292 at the south shore at Bonneville Dam, 0.1423 for the north shore at The Dalles, and 0.0890 for the north

shore at John Day Dam (Calvin 1975). Fields et al. (1964) reported that about 10% of the fish that used the east fishway at The Dalles Dam during a 1963 study were counted at night. During a similar study at McNary Dam, Fields et al. (1964) determined that fish counted over the south fishway at night were those that had entered during the daylight and no new fish entered the fishway after dark. During an adult passage evaluation study in 1985, 88 chinook and sockeye salmon with radio transmitters were tracked over McNary Dam, and 9 of the fish entered the fishways at night (Shew et al. 1985). The nine fish waited until morning to exit the fishways, using an average of 11.7 h to pass through the fishways, versus 2 to 4 h for fish that entered and passed through the fishway during the day.

There is, however, record of at least one salmon stock that used fishways exclusively at night. Fields et al. (1955) reported that sockeye salmon ascended the University of Washington fishway in Seattle mainly at night during a 1955 study. For the study period, 3 fish were counted during daylight hours, 116 on dark nights, and 26 on nights when the fishway was lit.

In general, salmon and steelhead readily migrate up through ladder sections with overflow weirs and submerged orifices, and sections with vertical-slot weirs (Monk et al. 1989; Stuehrenberg et al. 1979). Chinook salmon with radio transmitters (17 fish) that were tracked over Lower Granite Dam in May and June of 1975 averaged 4 h to pass through the fishway versus an average of 73 h spent at the dam (Liscom and Monan 1976). During a similar study conducted in May of 1973, 20 chinook salmon with radio

transmitters were tracked at Lower Monumental Dam (Monan and Liscom 1974b). The 20 fish were released in two groups of 10 fish each, during average river flows of 39.2 kcfs for the first ten fish released and 76.9 kcfs during the second group. The 10 fish from the first group required an average of 42 h to cross Lower Monumental Dam, of which an average of only 44 min were spent in the north-shore (powerhouse) fishway (8 fish) and 138 min in the south-shore (spillway) fishway (2 fish). Eight of the fish from the second release group passed the dam in an average of 84.3 h; 49 min in the north-shore fishway (5 fish), and 208 min in the south-shore fishway (3 fish).

Although the passage times through the fishways were not provided, Turner et al. (1984) did note that a number of fish moved back down in the fishways after partial ascensions. Of 35 fish crossing Ice Harbor Dam, 16 cases were observed where a fish partially ascended the fishway and then backed down, perhaps partly because of trapping operations at the top of the ladder. There were 9 cases of fish backing down the fishways at Lower Monumental Dam, 5 fish in the north-shore fishway and 4 in the south-shore fishway. In 1981, 2 of the 22 chinook salmon tracked over Little Goose Dam were known to have backed down and left the fishway, but later crossed the dam, and 8 fish backed down and left the Lower Granite fishway (Turner et al. 1983).

Passage times similar to those observed at Snake River dams have also been recorded during fishway evaluation studies at Columbia River dams. Spring and fall chinook salmon and sockeye salmon radio tracked over McNary Dam

averaged 2.4, 3.9, and 2.9 h, respectively, to pass through the fishways in a 1985 study (Shew et al. 1985). At John Day Dam passage through the powerhouse fishway by chinook salmon with radio transmitters generally took less than 3 h during a 1979-80 study (Johnson et al. 1982). Passage times through The Dalles Dam east fishway were estimated to be 3 to 4 h in the spring, and 4 to 7 h in the fall during a 1974-75 evaluation of the collection system (Duncan et al. 1978). During similar studies at Bonneville Dam, travel times through the fishways averaged 2 to 4 h in 1978 (Johnson et al. 1979), 2.7 to 5.1 h in 1982 (Ross 1983), and 3 to 4 h in 1984 (Shew et al. 1988). Passage rates through the Bonneville Dam fishways did not differ significantly between species, season, or fishway used.

In some instances, the time fish take to pass through a fishway has been longer than usually reported. During chinook salmon radio tracking studies to investigate areas of loss and delay at Bonneville Dam in 1971 and 1972, Monan and Liscom (1971; 1973) reported average passage times through the fishways of up to 64 h. These prolonged passage times appeared to be related to river flows. In 1972, 10 fish tracked during average river flows of 314 kcfs required 101 h to cross Bonneville Dam, of which 22 h were spent in the fishways. During the second release eight chinook salmon crossed the dam in an average of 181 h, with 64 h in the fishways, and average river flows of 484 kcfs. The longer travel times through the fishways may have been related to the high numbers of fish (8/18) which backed back down the ladders (Monan and Liscom 1973). During 1971, 10 chinook salmon averaged 63 h in the fishways while

crossing Bonneville Dam, and the times were reported to increase with river flows, and perhaps been related to the high nitrogen saturation levels (127 to 132%) in the area during the study (Monan and Liscom 1971).

Passage Through the Navigation Locks

A small number of upstream migrating fish bypass the fishways and pass dams through the navigational locks. A comprehensive study was conducted at Bonneville Dam to determine the number of fish passing through the navigational lock during the 1969 migration season (Monan et al. 1970). For this study, fish in the lock were sampled using a purse seine, tagged, released, and recaptured to get an estimate of the number of fish passing through the lock during each closure. Monan et al. estimated that 213 sockeye salmon (0.86%), 524 steelhead (1.1%), and 745 chinook salmon (1.3%) passed through the navigational lock during the 1969 season. In comparison, in an 1983 evaluation of the passage facilities at Ice Harbor Dam, two of the 37 (5.4%) radio tagged spring chinook salmon tracked over the dam passed through the navigational lock (Turner et al. 1984). During a similar study at John Day Dam in 1985, two radio tagged chinook salmon (1.7%) were also tracked through the navigational lock (Shew et al. 1985).

Fallback At Dams

Salmonids exiting fishways at the top of dams may not immediately continue to move upstream. Whether this is because the fish are resting after ascending up the ladder, or because they are temporarily

confused by the sudden loss of guiding river flow in the forebay of the dam is unknown. Fish milling about in the forebay can move into the spillway or turbine intakes and be swept back over or through the dam, an event referred to as fallback.

Fallback has been documented at both Snake and Columbia River dams (Table 2). In May of 1964, 223 chinook salmon with radio transmitters were released into the fishways at Ice Harbor Dam to determine patterns of fallback, and 23 of the fish (10.3%) fell back through the spillway (Johnson 1964). Of the 159 fish that crossed over the dam via the south shore fishway, 11 (6.9%) fallback, and 12 of the 64 fish (18.7%) that passed up the north-shore fishway fallback. During the low flow period (total flow < 150 kcfs, spill < 100 kcfs) the frequency of fallback was 3.5% from the south fishway and 18.7% from the north fishway. During the 8 d high flow period (flow > 150, spill > 100 kcfs) no fish were released from the north fishway, but fallback from the south fishway increased to 15.5%, and significantly more fish approached the spillway during the high flows than during the lower flows. In general, fallbacks occurred through the spillbays closest to the fishway exits, and specifically through bays 2 and 9. The lower fallback through bays 1 and 10 was probably due to the smaller openings (1 to 1.4 ft) of those gates during the study. Johnson estimated that about half of the fallback salmon reascended the dam after delays of 1 to 13 d.

In a 1976 and 1977 study to evaluate fallback at Little Goose Dam (Haynes and Gray 1980), 14 of 35 chinook salmon with radio transmitters that were tracked over

Little Goose Dam fell back an average of 1.6 times per fish.

During a spring 1975 study investigating the effects of spillway deflectors on adult passage, 30 chinook salmon were tracked at Lower Granite Dam during average spills of 105 kcfs (Liscom and Monan 1976). Of the 17 fish tracked over the dam, 3 (17.6%) fell back over the dam through the spillway. All three fish later recrossed the dam, but one of the fish was observed to have severe injuries.

In a 1981 radio tracking study, 258 steelhead and 32 chinook salmon were tracked from Lower Monumental to Little Goose Dam during mid July through September (Liscom et al. 1985). Of the 258 steelhead released upstream from Lower Monumental Dam, 52 (20.1%) fell back through the navigational lock, the turbines, or down the fishways (there was no spill at the time), and 23 of the fallback fish were known to have recrossed the dam. Later, 157 of these steelhead crossed Little Goose Dam, of which 6 (3.8%) fell back (two twice), and 3 recrossed the dam. Of the 32 chinook salmon released, 3 (9.4%) fell back and did not recross Lower Monumental Dam, and 1 of 13 (7.7%) later fell back and recrossed Little Goose Dam.

Fallbacks were also recorded during the 1981 and 1982 fish passage evaluations of the Snake River dams (Turner et al. 1983; 1984). In 1981, chinook salmon were outfitted with radio transmitters and released downstream from Little Goose Dam and tracked until they passed over Lower Granite Dam. Of the 36 fish released, 22 crossed Little

Table 2.-Salmon and steelhead fallback rates at Columbia and Snake River dams. Rates represent fraction (and percentage) of tagged fish observed to fallback over the dam during a study.

Species	Dam	Fallback rate	Source	Comments
Sockeye	Bonneville	2/9 (22.2)	Ross 1983	Summer 1982, one fell back twice
Sockeye	John Day	1/24 (4.2)	Shew et al. 1985	1985
Sockeye	McNary	2/9 (22.2)	Shew et al. 1985	1985
Steelhead	Lower Monumental	52/258 (20.1)	Liscom et al. 1985	1981, no spill at the time
Steelhead	Little Goose	6/157 (3.8)	Liscom et al. 1985	1981
Steelhead	Bonneville	2/4 (50.0)	Monan & Liscom 1975	1974
Steelhead	Bonneville	0/35 (0.0)	Liscom et al. 1978	Spring 1977, low flows
Steelhead	Bonneville	1/20 (5.0)	Ross 1983	Summer 1982
Chinook	Ice Harbor	23/223 (10.3)	Johnson 1964	1964, increased with flow
Chinook	Ice Harbor	4/43 (9.3)	Turner et al. 1984	Spring 1982, spill = 30-100 kcfs
Chinook	Little Goose	14/35 (40.0)	Haynes & Gray 1980	1976, 1977, multiple fallbacks
Chinook	Little Goose	1/22 (4.5)	Turner et al. 1983	1981, spill = 14-60 kcfs
Chinook	Lower Monumental	3/32 (9.3)	Liscom et al. 1985	1981
Chinook	Lower Monumental	1/13 (7.7)	Liscom et al. 1985	1981
Chinook	Lower Monumental	4/36 (11.1)	Turner et al. 1984	Spring 1982, spill = 32.5-135 kcfs
Chinook	Lower Granite	3/17 (17.6)	Liscom & Monan 1976	Spring 1975, one was injured
Chinook	Lower Granite	1/25 (4.0)	Turner et al. 1983	Spring 1981, spill = 10-40 kcfs
Chinook	Bonneville	53/935 (5.7)	Horton & Wallace 1966	1966, estimated rate of 17.5%
Chinook	Bonneville	4/10 (40.0)	Monan & Liscom 1971	Spring 1971
Chinook	Bonneville	0/10 (0.0)	Monan & Liscom 1973	Spring 1972, spill = 314 kcfs
Chinook	Bonneville	1/10 (10.0)	Monan & Liscom 1973	Spring 1972 spill = 522 kcfs
Chinook	Bonneville	2/331 (0.6)	Young et al. 1974	Summer 1973, low flows
Chinook	Bonneville	3/834 (0.4)	Young et al. 1974	Fall 1973, low flows
Chinook	Bonneville	(36)	Young et al. 1975	Spring 1974

Table 2. Continued.

Species	Dam	Fallback rate	Source	Comments
Chinook	Bonneville	(26)	Young et al. 1975	Summer 1974
Chinook	Bonneville	8/35 (22.9)	Monan & Liscom 1975	Spring 1974, one by nav. lock
Chinook	Bonneville	7/18 (38.8)	Monan & Liscom 1975	Summer 1974, two through powerhouse
Chinook	Bonneville	(34)	Young et al. 1977	Spring & summer 1975
Chinook	Bonneville	5/39 (12.8)	Monan & Liscom 1976b	Summer 1975, spill = 68 kcfs
Chinook	Bonneville	9/28 (32.1)	Liscom et al. 1977	Spring 1976, estimated rate of 19%
Chinook	Bonneville	(31)	Young et al. 1978	Spring 1976 spill = 155 kcfs
Chinook	Bonneville	(39.2)	Young et al. 1978	Summer 1976 spill = 148 kcfs
Chinook	Bonneville	(0.0)	Young et al. 1978	1977, low flows, spill = 0-6 kcfs
Chinook	Bonneville	2/90 (2.2)	Liscom et al. 1978	1977, low flows, one thru turbines
Chinook	Bonneville	(15)	Gibson et al. 1979	Spring 1978, spill = 97 kcfs
Chinook	Bonneville	(3)	Gibson et al. 1979	Summer 1978, spill = 76 kcfs
Chinook	Bonneville	6/300 (2.0)	Liscom, Stuehrenberg 1983	Fall 1982
Chinook	Bonneville	10/41 (24.4)	Ross 1983	Spring 1982, flow = 321 kcfs, one
Chinook	Bonneville	3/20 (15.0)	Ross 1983	Summer 1982, flow = 327 kcfs
Chinook	Bonneville	0/40 (0.0)	Ross 1983	Fall 1982, flows = 147 kcfs
Chinook	Bonneville	7/68 (10.3)	Turner et al. 1984	Spring 1983
Chinook	Bonneville	19/146 (13.0)	Shew et al. 1988	Spring 1984
Chinook	The Dalles	31/213 (14.6)	Monan & Johnson 1974	Fall chinook
Chinook	The Dalles	2/200 (1.0)	Liscom, Stuehrenberg 1983	1982
Chinook	The Dalles	6/44 (13.6)	Johnson et al. 1982	1980
Chinook	McNary	2/133 (1.5)	Liscom, Stuehrenberg 1983	1982
Chinook	McNary	1/45 (2.2)	Shew et al. 1985	Spring 1985
Chinook	McNary	2/34 (5.9)	Shew et al. 1985	Summer 1985
Chinook	John Day	3/40 (7.5)	Johnson et al. 1982	1982
Chinook	John Day	5/83 (6.0)	Shew et al. 1988	Spring 1984
Chinook	John Day	4/47 (8.5)	Shew et al. 1985	Spring 1985

Goose Dam, and 1 (4.5%) fish fell back and did not recross. Spills at Little Goose Dam during this period ranged from 14 to 60 kcfs. Twenty-five of these salmon later crossed Lower Granite Dam, and 1 (4.2%) of those fell back and then recrossed the dam. Spills at Lower Granite Dam ranged from 10 to 40 kcfs. Of 43 spring chinook radio tracked in 1982, 4 (9.3%) fell back over Ice Harbor Dam, and 1 later reascended the fishway. The spills at Ice Harbor ranged from 30 to 100 kcfs during the study. Of the 35 fish that crossed Lower Monumental Dam, 4 (11.4%) fell back, and all recrossed the dam. Spill at Lower Monumental Dam during the period ranged from 32.5 to 135 kcfs.

In a 1991 study of chinook salmon and steelhead migration in the lower Snake River (Bjornn et al. 1992), several steelhead captured at Ice Harbor dam, outfitted with radio transmitters, and released both upstream and downstream from the dam were subsequently located in the Columbia River upstream from the mouth of the Snake River. Some of the fish returned to the Snake River again, but others remained in the Columbia River. Large numbers of steelhead (>9,000 in 1991) have also been observed falling back at McNary Dam during the fall and early winter (Paul Wagner, Washington Department of Wildlife, personal communication).

Fallback has also been reported at Columbia River dams. The highest, and best documented, fallback rates in the Columbia River have been reported for Bonneville Dam. The prevalence of fallbacks at Bonneville Dam seems to be due to the unique configuration of the dam. In an early study investigating sources of

fish count discrepancies between Columbia River dams, 53 tagged spring chinook salmon that were part of a group of 935 fish released upstream from the dam during the spring of 1966, were observed at the Bonneville Dam counting stations (Horton and Wallace 1966). Horton and Wallace estimated total fallback of spring chinook salmon to be 17.5% in 1966, producing a counting error of 16.5%.

In 1971, 4 of 15 spring chinook salmon with radio transmitters released at Bonneville Dam fell back over the dam (Monan and Liscom 1971). During a similar study in 1972, 20 spring chinook salmon with radio transmitters were released downstream from Bonneville Dam and monitored up to The Dalles Dam (Monan and Liscom 1973). None of the first 10 fish released downstream from Bonneville Dam fell back over the dam, even though six of the eight fish exiting the Bradford Island fishway were tracked around the tip of the island and across the spillway area of the forebay before they turned and continued migrating upstream. Monan and Liscom suggested that these fish were attracted to the spill area by a counter eddy which flowed upstream along the north shore of the island during low flow conditions (314 kcfs). During the second release, 8 of 10 fish crossed Bonneville Dam. Seven fish used the Bradford Island fishway, and only 1 swam to the spillway and fell through during flows of 522 kcfs. The fallback fish later recrossed the dam. The eddy present previously had evidently been eliminated by the higher flows.

During 1973, studies were initiated to determine mortality, delay, and the effects

of peaking flows on adult passage conditions in the lower Columbia River. Spring, summer, and fall chinook salmon were tagged and released at Bonneville Dam to be counted at upstream dams (Young et al. 1974). Of 331 summer chinook salmon and 834 fall chinook salmon released upstream from Bonneville Dam, two and three fish, respectively, were recounted at the dam. None of the tagged spring chinook salmon released were reported as being captured a second time at Bonneville Dam. Young et al. (1974) suggested that the low fallback rate (less than 1%) was due to the low flows that year (average daily was 134 kcfs).

When the study was repeated in 1974, the fallback rate at Bonneville Dam was estimated to be 36% for spring chinook and 26% for summer chinook salmon (Young et al. 1975). Again, most of the fallbacks were of fish exiting the Bradford Island fishway. Young et al. (1975) suggested that fallbacks may be the major source of delays for migrating salmonids at Bonneville Dam.

During a second 1974 study, spring chinook salmon, summer chinook salmon, and steelhead were radio tracked at Bonneville Dam to determine the effect of fallback and spillway deflectors on adult passage (Monan and Liscom 1975). During this study eight of the 35 (23%) spring chinook salmon tracked over the dam fell back, seven that had used the Bradford Island fishway, and one the Washington-shore fishway. Seven of the fish passed back through the spillway and one through the ship lock, and all later recrossed the dam. Flows averaged 335 kcfs during the spring segment of the study. During the early summer (flows

averaged 566 kcfs), 7 of 18 (39%) summer chinook salmon fell back at Bonneville, 5 through the spillway and two through the powerhouse, of which six recrossed the dam and one died. Two of four (50%) steelhead fell back through the spillway, and did not recross.

In 1975, Young et al. (1977) again found fallback to be high at Bonneville Dam, 34% for tagged spring and summer chinook salmon. In a 1975 study conducted with radio-tagged summer chinook salmon and steelhead to investigate sources of loss and delay and the effects of peaking flows at Bonneville and The Dalles dams (Monan and Liscom 1976), 5 of 39 summer chinook salmon tracked over Bonneville Dam fell back with spill ranging from 2 to 159 kcfs. Four of the fallback salmon later recrossed the dam. No fallbacks occurred at The Dalles Dam.

In April and May of 1976, an attempt was made to decrease fallback at Bonneville Dam by placing a 150 ft long deflector net upstream from the Bradford Island fishway exit (Liscom et al. 1977). The purpose of the net was to divert fish away from the Bradford Island shoreline to prevent them from circling around to the spillway, as had been observed in previous studies. The effectiveness of the deflector net was tested by tracking 67 radio-tagged spring chinook salmon released at various sites. Of the 28 fish released downstream from Bonneville Dam, nine fell back through the spillway and seven reascended the dam (one recrossed twice and one recrossed three times). Of the 14 fish released upstream from the Bradford Island deflector net, nine moved to the spillway and four fell back. Four fish were released in mid-channel upstream from the

powerhouse and only one moved toward the spillway, but did not fall through. Of the nine fish released from the Oregon shore, none swam near the spillway. Fourteen of the 28 fish released downstream from the dam exited from the Bradford Island fishway, and 12 of those fish circled around the island and continued on to the spillway. Fallbacks occurred across the entire spillway. Liscom et al. (1977) estimated fallback to be 19% during the spring 1976 study, 24% of the fish using the Washington-shore fishway and 18% of those using the Bradford Island fishway. They concluded that the deflector net was ineffective at reducing fallback, and suggested moving the fishway exit closer to the Oregon shore to improve passage conditions at Bonneville Dam.

In the late spring and summer of 1976, a similar study was conducted using a longer deflector net (250 ft) at the same location (Young et al. 1978). During this study 1,000 flag-tagged spring chinook salmon and 957 summer chinook salmon were released upstream and downstream from the dam at similar locations as used in the previous study. From their observations, Young et al. (1978) estimated fallback was 31% for spring chinook salmon at 155 kcfs average spill, and 39.2% for summer chinook salmon during average spills of 148 kcfs. There was a 60-66% fallback rate for fish released upstream from the deflector net and 18% fallback for fish released from the Oregon shore. The deflector net was again judged to be ineffective and an Oregon shore exit for the fishway was suggested.

Fallback at Bonneville Dam was found to be negligible during 1977, probably due

to the low flows and spill (0-6 kcfs) that occurred that year (Young et al. 1978). This result was verified by Liscom et al. (1978) during their spring 1977 radio tracking study investigating areas of loss and delay of salmonids between Bonneville and John Day dams. Liscom et al. reported that of 90 spring chinook salmon and 35 steelhead tracked across Bonneville Dam, only 2 salmon (2%) fell back. One of these fish passed through the turbines and died, the second passed through the spillway and did not reascend the dam. No steelhead fell back at Bonneville, and no fallbacks were observed at The Dalles or John Day dams. Liscom et al. noted that tagged fish entering tributaries tended to overshoot the rivers by 12 to 15 miles. They suggested that tributary overshoot may be one explanation for fallbacks, that is, a fish crossing a dam may have travelled too far upstream and thus returns back downstream, over the dam, to enter its natal spawning tributary.

Fallback was again observed during the spring and summer of 1978 (Gibson et al. 1979). In this study, 898 spring and 881 summer chinook salmon were tagged with anchor tags and released upstream and downstream from Bonneville Dam and counted at Bonneville, The Dalles and John Day dams to determine mortality and fallback rates. Fallback was estimated to be 15% for spring chinook salmon during average spills of 97 kcfs, and 3% for summer chinook salmon during average spills of 76 kcfs. Deflector nets were tested at both fishways during this study. Gibson et al. concluded that the 106 m net placed upstream from the Bradford Island exit in 1978 was ineffective at reducing fallbacks, but a 122 m net placed parallel

to the north shore did seem to force fish exiting the Washington-shore fishway to move further upstream away from the spillway. No fallback was observed at John Day Dam and fallback rates could not be assessed at The Dalles Dam because of the fishery near the dam.

In 1982, two radio-tracking studies were conducted at Bonneville Dam. During the first study, transmitters were placed in 170 salmon and steelhead to evaluate the adult fish passage facilities at Bonneville Dam (Ross 1983). Of the 41 spring chinook salmon tracked over the dam, 10 (24.4%) fell back during average flows of 321.2 kcfs (spill = 31 to 199 kcfs) and 7 of the fallbacks recrossed the dam (one twice). Twenty summer chinook salmon were tracked over the dam, of which 3 (15%) fell back through the spillway and reascended the dam. Of the 20 steelhead released in the summer, 1 of 8 tracked over the dam while there was spill (up to 108 kcfs) fell back over the dams, but none of the 12 tracked when there was no spill fell back over the dam. Two of 9 sockeye salmon (22%) also fell back over and recrossed (one sockeye crossed twice) Bonneville Dam during summer flows that averaged 327.6 kcfs (spill = 2 to 250 kcfs). None of the 40 fall chinook salmon, or the 14 steelhead outfitted with transmitters in the fall fell back over the dam. Flows in the fall were about 147 kcfs with minimal spill (2.4 kcfs). In the second study, 286 fall chinook salmon were outfitted with transmitters to identify areas of loss and delay between Bonneville and McNary dams (Liscom and Stuehrenberg 1983). Six fish (2%) fell back at Bonneville Dam, two recrossed the dam, two returned to a hatchery, and two continued moving downstream. Two fish

fell back (< 1%) at The Dalles Dam, of which one fish died and the other continued downstream and fell over Bonneville Dam. Two fish fell back (1.5%) at McNary Dam and reascended the fishways.

The adult passage facilities at Bonneville Dam were evaluated again in 1983 using 69 spring and 41 fall chinook salmon, and 39 steelhead outfitted with radio transmitters (Turner et al. 1984). Sixty-eight of the spring chinook salmon were tracked over Bonneville Dam, of which 7 (10.3%) fell back through the spillway. Six of these fish had come from the Bradford Island fishway (14.6% of all fish passing dam) and 1 from the Washington-shore fishway (3.6%). None of the fall chinook salmon or steelhead fell back at the dam.

During a 1984 study of adult passage at Bonneville and John Day dams, 146 spring chinook salmon with radio transmitters were tracked upstream. Nineteen fish fell back (13%) at Bonneville Dam, 12 from the Bradford Island fishway and 7 from the Washington-shore fishway (Shew et al. 1988). All the fallback fish reascended the dam. Five fish (6%) fell back at John Day Dam and 2 recrossed the dam.

Monan and Johnson (1974) studied the movements of 213 fall chinook salmon outfitted with sonic transmitters to determine the amount of tributary turnoff and spawning occurring between The Dalles and McNary dams. Thirty-one of the fish (29%) released upstream from The Dalles Dam were later found downstream. The fish that fell back may have been destined for spawning areas or hatcheries

downstream from The Dalles Dam, and the movement over The Dalles Dam was temporary straying.

In 1980, 44 spring chinook salmon with radio transmitters were released upstream from The Dalles Dam and tracked upstream to evaluate the fish collection system at John Day Dam (Johnson et al. 1982). Six fish (13.6%) fell back over The Dalles Dam, and 3 recrossed the dam. Forty of these fish later crossed over John Day Dam, of which 3 fell back and 1 recrossed that dam.

In 1985, spring and summer chinook and sockeye salmon with radio transmitters were used to evaluate the passage facilities at John Day and McNary dams (Shew et al. 1985). Four of 47 (8.5%) spring chinook salmon, and 1 of 24 sockeye salmon (4.2%) fell back over John Day Dam. At McNary Dam, 1 of 45 (2.2%) spring chinook salmon fell back through the spillway and that fish later recrossed the dam. Two of 34 (5.9%) summer chinook salmon, and 2 of 9 (22%) sockeye salmon fell back through the turbines or the

juvenile bypass, of which 1 chinook and 1 sockeye salmon recrossed the dam.

In summary, a significant number of the adult salmon and steelhead passing over dams have been observed to fall back over certain dams. High fallback rates are usually associated with high river flows and spill at the dams, and the location of fishway exits relative to the spillways. Fallback at some dams may also be a correction by some fish in their migration path. Some stocks of fish have a natural tendency to wander during their migration and may pass over dams or enter tributaries that are not the most direct route to their home streams (Bjornn et al. 1992). Liscom et al. (1979) concluded from several fallback studies conducted from 1971 through 1979, that fallback rates can be high at times, but few fish are injured or die as a direct result of falling back over a dam. Adults falling back over a dam can lead to inaccurate fish counts at dams (positive bias), and migration times are increased if the fish must reascend the dam.

Migration In Reservoirs

The effect of impounding sections of free flowing Columbia and Snake rivers on the migration rates and behavior of adult salmon and steelhead appears to have been minimal. Migrants have not been seriously disorientated by reduced currents in run-of-river reservoirs. Adult salmonids passed through the Snake River reservoirs at similar or faster rates than through the unimpounded river (Table 1; Stabler et al. 1981; Trefethen and Sutherland 1968). Steelhead and chinook salmon typically traveled through the reservoirs during the

day, and along the shore lines in water 20 to 30 ft deep (Eldred 1970; Strickland 1967a; 1967b). Steelhead moved slower and held longer in the reservoirs as the water temperatures decreased in winter (Monan et al. 1970), and preferred overwintering in free flowing stretches of river when possible (Stabler et al. 1981).

During an initial study in September and October 1967, six steelhead with sonic transmitters were tracked through the Ice Harbor pool to determine their migration behavior within reservoirs (Strickland

1967b). In general, the tagged steelhead moved away from Ice Harbor Dam (RM 9.7, river mile) on the morning of release, and travelled along the south shore until they reached RM 22 to 26 that evening. All the fish stopped moving at night and held in the deep mid-channel areas. The fish continued migrating upstream the next morning between sunrise and 11 am, moved along the south bank until reaching RM 33 to 40, and then stopped just before reaching Lower Monumental Dam. The steelhead tended to move near shore, in water 6 to 9 m deep, and at a rate of 1.3 km/h (16 to 24 km/d).

In a similar study completed in 1969 with 20 steelhead outfitted with radio transmitters and tracked within the Ice Harbor pool, 8 were released in September and October (3 of these were lost), 8 were released in November, and 4 were released in December (Eldred 1970; Monan et al. 1970). The migration paths used by these fish were similar to those observed in the 1967 study. The fish initially moved upstream along the south shore to a milling area at RM 15. From there they would move along the south bank to the second milling area at RM 21-23, where many would hold for the night. Between RM 24 and 25 the fish would cross over to the north shore, then cross back to the south shore at RM 27, and continue on to the next milling area between RM 29 and 31. The fish would continue upstream in this manner until reaching Lower Monumental Dam. The tagged steelhead generally swam within 3-30 m of shore, in water 6-12 m deep, and averaged 1.26 km/h (12 to 50 km/d). In September the fish swam fastest and nearer the bottom, but as temperatures dropped in November and December they

swam slower, resting more often, and nearer the surface. Only one of the four fish released in December moved away from Ice Harbor Dam.

In 1975 and 1976, migration of adult salmon and steelhead was studied in Lower Granite Reservoir following its closure in February of 1975 (Stabler et al. 1981). In the summer of 1975, 31 chinook salmon were outfitted with radio or sonic transmitters and tracked through the Snake-Clearwater rivers confluence area. Chinook salmon tracked in the summer (June and July) of 1975 had migration rates of 1.2 km/h in the impounded areas. Stabler et al. concluded that impoundment by Lower Granite Dam did not produce a detrimental effect on salmon migrations in summer. While investigating the effect of spillway deflectors on adult passage, Liscom and Monan (1976) reported that chinook salmon with transmitters averaged 1.6 km/h between Little Goose and Lower Granite dams in the spring of 1975.

Fifteen steelhead were radio tracked from Lower Granite Dam in September and October of 1975 through the Snake-Clearwater confluence. Four of the steelhead that were destined to continue up the Snake River moved into the Clearwater River, and stayed for 4 to 18 d before eventually re-entering the Snake River and continuing upstream, perhaps because the Clearwater River was cooler than the Snake River during the early fall. Migration rates of the tagged steelhead averaged 12.8 km/d, similar to rates reported for this section of river prior to impoundment (Falter and Ringe 1974). Time to travel through the reservoir averaged 4 d. Prior to impoundment, steelhead had used the Snake River for

overwintering. Following impoundment, some of the 25 steelhead outfitted with transmitters overwintered in the upper section of Lower Granite Reservoir, but most of the fish moved further upstream into the free flowing river sections. Stabler et al. (1981) concluded that impoundment by Lower Granite Dam had altered the quality of this area as overwintering habitat for steelhead.

In 1975 and 1976 studies of peaking flows and adult passage, McMaster et al. (1977) measured migration rates of chinook salmon and steelhead in the Snake River. Of 12 chinook salmon released at Ice Harbor Dam in July with radio transmitters, 8 migrated to Lower Monumental Dam at rates of 11.1 to 35.6 km/d, and 3 traveled to Little Goose Dam at rates of 8.4 to 20.4 km/d. The migration rate from Ice Harbor to Little Goose dams of 22 magnetically tagged chinook salmon released upstream from Ice Harbor Dam in July averaged 11.8 km/d with flows in the Snake River of <80 kcfs.

Migration rates for steelhead in 1975 between Ice Harbor and Lower Monumental and Little Goose dams was studied during September through November (McMaster et al. 1977). Of 48 steelhead with radio transmitters released at Ice Harbor Dam, 37 migrated to Lower Monumental Dam at an average rate of 20.9 km/d, and 32 migrated to Little Goose Dam at a rate of 16.7 km/d, the lesser rate reflected time to pass Lower Monumental Dam. The migration rate for 199 magnetically-tagged steelhead between Ice Harbor and Little Goose dams averaged 12.5 km/d.

Haynes and Gray (1980) reported migration rates of 2 to 5 km/h for 35 chinook salmon with radio transmitters in the Snake River during a 1976-77 study to investigate delay and fallback at Little Goose and Lower Granite dams.

Bjornn and Ringe (1980) recorded the migration rates of steelhead from McNary Dam up the Snake River during a 1978 study investigating sources of loss and delays in the McNary pool area during summer and fall. They found that steelhead with radio transmitters averaged 5.5 km/d to Ice Harbor Dam (96 fish), and 7.8 to 10.4 km/d to Lower Granite Dam (87 fish).

In their evaluation of adult passage at the Snake River dams in 1981 and 1982, Turner et al. (1983; 1984) measured migration rates for spring chinook salmon of 56.3 km/d in the reservoir between Little Goose and Lower Granite dams (21 fish), and 56.0 km/d from Ice Harbor to Lower Monumental Dam (38 fish).

In a 1991 study of spring and summer chinook salmon migration rates in the lower Snake River reservoirs (Bjornn et al. 1992), fish with radio transmitters ($n = 172-211$) migrated at rates of 56 to 62 km/d in the reservoirs between the four dams. Migration rates of the salmon in the free flowing rivers upstream from the reservoirs were about half that observed in the reservoirs. River flows and turbidity were relative low in 1991.

The effects of reservoirs on salmonid migrations have also been investigated in the Columbia River. The effect of dams on the migration rates of sockeye salmon was studied by Raymond (1966) through an

analysis of fish counts at dams from 1938 to 1963. He found that sockeye salmon migrated between Bonneville and Rock Island Dam in an average of 17 d (28.4 km/d) during 1938-50 (no dams), and 19 d (25.3 km/d) during 1951-63 (up to three dams between Bonneville and Rock Island dams). In summer 1948, Schoning and Johnson (1956) reported that 74 tagged chinook salmon travelled from Bonneville Dam to Celilo Falls in an average of 8.1 d (9 km/d). In 1955, tagged spring chinook salmon migrated from the mouth of the Columbia River to Celilo Falls at an average rate of 15.1 km/d (Wendler 1964).

A study was conducted in 1956 and 1957 to assess the effect of The Dalles Dam on salmonid migrations (Oregon Fish Commission 1960a). In 1956, prior to completion of The Dalles Dam, tagged fish released at Bonneville Dam and recovered at McNary Dam had migration rates of 7.9 km/d for spring chinook salmon, 25.1 km/d for summer chinook salmon, 22.7 km/d for fall chinook salmon, 20 km/d for sockeye salmon, 19.5 km/d for coho salmon, and 14.6 km/d for steelhead. After closure of the Dalles Dam in 1957 the migration rates were 25.9 km/d for the summer chinook salmon, 27.2 km/d for fall chinook salmon, and 27.8 km/d for sockeye. The higher travel rates during the second year of the study were attributed to more favorable river conditions in 1957, and to the inundation of Celilo Falls by The Dalles pool.

In 1957, 43 adult salmonids were outfitted with sonic transmitters and tracked above Bonneville Dam to observe the movement patterns of salmonids in the forebay of a dam (Johnson 1960). Of the 37 fall chinook and 2 coho salmon, and 4

steelhead released just upstream from the spillway, 23 fish were tracked 16 km upstream until the signal was lost. Following release the fish moved away from the dam at time intervals ranging from 1 min to 5 h. Most of the fish travelled along the Washington shore, in water of 9 m depth or less, and at rates of about 2 km/h.

From 1973 to 1978 in a study to measure migration rates of adult salmon and steelhead between Bonneville and Little Goose dams (Gibson et al. 1979), 23,154 spring chinook and 8,297 summer chinook salmon, and 8,014 summer steelhead were tagged and released from the Washington shore fishway at Bonneville Dam. Migration rates for chinook salmon to Little Goose Dam averaged 21.6 km/d in 1973 (low flow year), and 15.2 km/d and 14.7 km/d during 1974 and 1975 (high flow years). Late spring chinook salmon tended to travel slower than early summer chinook salmon under similar flow conditions. The degree of overlap between the two chinook salmon runs at Little Goose Dam was 15% in 1974 and 23% in 1975. Steelhead averaged migration rates of 20.5 km/d in late July, and 8.2 km/d in early August of 1974. In 1973 spring chinook salmon travelled from Bonneville to McNary Dam at rates of 18 km/d, and fall chinook salmon migrated at 20 km/d (Young et al. 1974). In 1974, the spring chinook salmon moved between Bonneville and The Dalles dams at 21 km/d, and the summer chinook salmon migrated at 12 km/d (Young et al. 1975). In 1975, chinook salmon averaged 50.8 km/d between John Day and McNary dams (Young et al. 1977). And in 1978, Gibson et al. (1979) reported that summer

chinook migrated between Bonneville and The Dalles dams at 17.8 km/d.

During the summer of 1975, 47 summer chinook salmon and four steelhead were radio tracked over Bonneville and The Dalles to determine areas of loss and delay and investigate the effects of peaking flows on adult passage in the lower Columbia River (Monan and Liscom 1976b). During this study 38 chinook salmon and one steelhead were tracked from Bonneville Dam to The Dalles Dam in 30 h (2.5 km/h). In a similar study in 1977, Liscom et al. (1978) reported travel rates of 1.6 km/h for chinook salmon and 1.3 km/h for steelhead between Bonneville and John Day dams.

The effects of Brownlee Reservoir, a deep storage reservoir, on upstream migrations of fall chinook salmon was assessed by releasing tagged salmon into the Brownlee Dam forebay and in the Snake River upstream from the reservoir and then tracking the fish to the spawning grounds (Trefethen and Sutherland 1968). These salmon migrated at average rates of 16.8 km/d in 1960, and 16.1 km/d in 1962 while traveling through the reservoir. Fifty-nine sonically tagged chinook salmon successfully migrated through the reservoir at rates of 2 to 19 km/d. From surveys, it was determined that there was no significant difference in the numbers of fish reaching the upriver spawning grounds between the two release sites (Raleigh and Ebel 1968; Trefethen and Sutherland 1968).

Tagged sockeye salmon were also used to determine the effects of Rocky Reach Dam on salmonid migrations (Major and Mighell 1966). In 1953 and 1954

(before Rocky Reach Dam was constructed) tagged sockeye salmon released at Rock Island Dam travelled at rates of 26.4 to 39.7 km/d to Zosel Dam, 238 km upstream. Tagged sockeye salmon covered the same distance at 9.5 to 33.9 km/d in 1962 and 1963, after completion of Rocky Reach Dam. Major and Mighell concluded that Rocky Reach Dam had little effect on migrating sockeye salmon. In a 1965 study of steelhead, eight fish with sonic transmitters were tracked through Rocky Reach Reservoir and found to travel at an average rate of 1.6 km/h (Strickland 1967a). Eight sockeye salmon moved from Bonneville to Rocky Reach Dam at rates of 16 to 32 km/d in 1966, in a study to determine sources of salmonid losses in the Columbia River (Horton and Wallace 1966).

A sonic tagging study was carried out in 1965 to determine steelhead migration patterns in Rocky Reach Reservoir (Strickland 1967a). Of the 18 tagged steelhead released, eight were tracked through the entire length of the reservoir. The tagged steelhead moved through the reservoir at rates of about 1.6 km/h. Migrations were interrupted by resting periods lasting from 15 minutes to several hours. They would also tend to rest more and travel slower on reaching the faster flowing waters near the head of the reservoir. Most of the fish swam near the shores in water 7.5 to 10.7 m deep.

Flows

The volume of water flowing through run-of-the-river type reservoirs has been a matter of concern for adult and juvenile salmonid passage. Generally the concern

for adult migrants has been the low flows during part of each day that have been released from dams to save water for electrical power generation at daily periods when power demand is highest. Near-zero flow at night has been proposed and practiced in the lower Snake River. Because some adult salmon and steelhead slow their migration at night in the Columbia and Snake rivers (Strickland 1967b; Eldred 1970; Monan et al. 1970), managers theorized that reducing the flows at night may have minimal effects on migration rates. Others were concerned that reduced flows might delay the upstream migration of the fish.

An evaluation of zero flow at night from two dams in the lower Snake River occurred in 1975 and 1976 (McMaster et al. 1977). Alternating weeks of "normal" (10,000) versus zero flow at night was set up at Lower Monumental and Little Goose dams during the summer and fall of 1975. Chinook salmon and steelhead were tagged (magnetic tags or radio transmitters) and released to migrate through the reservoirs during the two flow-at-night conditions. Six of the 20 radio-tagged chinook salmon released in the summer of 1975, and 27 of the 48 radio-tagged steelhead released in the fall were tracked from Ice Harbor, or Lower Monumental Dam, to Little Goose Dam. There were also 94 and 312 magnetic-tagged chinook salmon and steelhead released at Ice Harbor Dam, of which 28% and 67% were recovered at Little Goose Dam, respectively. McMaster et al. (1977) concluded that there was no difference in the behavior or migration rates of the tagged salmon and steelhead during the 8 hour nighttime periods of near-zero flows (generally less than 200 cfs), control flows

(10 or 20 kcfs), and uncontrolled flows (12.8 to 63 kcfs). They also found that the numbers of fish counted at the three dams during 1976 were not significantly different between periods of zero and 20 kcfs nighttime flows.

Zero nighttime flows in the Snake River had been limited to 7 h at night between December and March, a period when few fish were migrating. The results reported by McMaster et al. (1977) prompted the Bonneville Power Administration to request an extension of the period when zero flows would be allowed to 9 h a night and to weekends, from August through April. This request led to a more extensive radio-tracking study conducted in 1982 to investigate the effect of zero flows at night on the migration of adult summer and fall chinook salmon and steelhead in the lower Snake River (Liscom et al. 1985). In this study, 258 steelhead and 32 chinook salmon were tracked from Lower Monumental to Little Goose Dam during alternating periods of zero flows (200 cfs or less) lasting 7 h nightly and up to 24 h on the weekends and normal nighttime flows. Liscom et al. found that travel times to Little Goose Dam were significantly longer during zero than during control flows. The tagged steelhead averaged 120 h to reach Little Goose Dam during zero flow periods, as compared to a mean of 79 h during control periods. Travel times for chinook salmon averaged 70 h during zero flows versus 40 h during control periods. More of the fish that reached Little Goose Dam also tended to move back downstream for periods of time during zero nighttime flows (54%) than during normal flows (25%). Liscom et al. recommended that zero flows

not be used during periods of adult migrations.

High flows through reservoirs may slow the upstream migration of salmon and steelhead, especially when combined with high turbidity, but there is little evidence available at present on the effects of higher flows. During a 1972 study, Monan and Liscom (1973) radio tracked 14 spring chinook salmon from Bonneville to The Dalles Dam at rates of 25.7 to 35.4 km/d in river flows that ranged from 209 to 225 kcfs, and three fish at rates of 8.0 to 12.9 km/d in flows of 417 kcfs.

Temperatures

Water temperatures influence the rate of upstream migration and timing of passage of salmon and steelhead in the Columbia and Snake rivers. Chinook salmon and steelhead usually slow their migration in the Columbia River and delay entering the Snake River when water temperatures are high in the summer and early fall (Stuehrenberg et al. 1978). As fall proceeds and water temperatures drop, the fish resume their migration. The fall chinook salmon spawn and die, but the steelhead migrate part way to the spawning grounds before stopping their migration for the winter as temperatures reach 4-5°C (Stabler et al. 1981; Falter and Ringe 1974).

During an early study (1967-68) of loss and delays of migrating salmonids in the Columbia and Snake rivers, Stuehrenberg et al. (1978) reported that summer chinook salmon and steelhead with radio transmitters tended to congregate just downstream from the confluence of the

Columbia and Snake rivers from mid-July to late August. During the summer the temperature of Snake River water increases faster than Columbia River temperatures. In July when concentrations of fish were forming, Snake River temperatures were 22°C, as compared to 17°C in the Columbia River. By 2 August, the water temperature was 26°C in the Snake River, and 22°C in the Columbia River. The blockage of fish diminished in late August when water temperatures had declined to 21°C in both rivers. At the peak of the blockage in 1967 an estimated 2,000 steelhead were holding in the Columbia River near the mouth of the Snake River. Following the temperature decrease in early September, steelhead counts at Ice Harbor increased by nearly an order of magnitude. The delays were due to the high Snake River temperatures, which were near the lethal limit for salmonids, but also by the differential of temperatures in the two rivers.

Turbidity

Turbidity of the water passing a dam also affects adult fish passage; with high turbidities (secchi disk visibilities <0.6 m) the fish virtually cease migrating (Davidson 1957; Bjornn and Rubin 1992), perhaps because of impaired visibility. High turbidities often accompany the initial peak flows during the spring snowmelt runoff, so that a combination of high flows and high turbidities often disrupt the upstream migration of spring chinook salmon.

Nitrogen Supersaturation

Hydroelectric development of the Columbia and Snake rivers produced a new hazard for upstream migrants in the form of nitrogen gas supersaturation in the water. Water flowing over spillways and plunging into deep pools at the base of dams increases the saturation of nitrogen in the water (up to 146%, Ebel 1971; Gray and Haynes 1977) which led to significant mortalities and delays at Columbia and Snake River dams (Beiningen and Ebel 1970; Ebel 1970). Chinook salmon that migrate deep in the Columbia or Snake river reservoirs and then move up near the surface may develop nitrogen gas bubble disease if the waters are highly saturated (Ebel et al. 1975).

One of the early reports of nitrogen supersaturation was by Westgard (1964) who reported that 119% nitrogen saturation produced blindness from gas bubble disease in 34% of the adult spring chinook salmon in the McNary spawning channel in 1962. Blinded adults had difficulty spawning and an 82% higher pre-spawning mortality rate than fish not blinded. In this case the nitrogen saturation was due to the design of the water inlet to the channel. Water entering the channel plunged over a weir, forcing gases into solution at depths.

Nitrogen supersaturation first became a concern in 1965 when concentrations as high as 125% were measured in the Columbia River (Ebel 1970). Prompted by this concern, a study was carried out in 1966 and 1967 to determine the source of the supersaturation conditions and the effects on migrant salmonids. In 1966 and 1967, water samples were collected from

26 sites on the Columbia River from Astoria to Grand Coulee Dam (including Ice Harbor Dam), from February to November. From his analysis Ebel concluded that supersaturation conditions were created by the entrainment of gases from the deep plunging of water spilled at the dams. This conclusion was confirmed during test spills at Bonneville Dam in 1966; nitrogen saturations increased from 100% to 125% in the spilled water, while saturation levels in water from the forebay and tailraces downstream from the turbine discharge remained constant. The increase in nitrogen saturation varied by dam and the levels were maintained between dams due the lack of circulation and the warming of the surface water in the forebays. Nitrogen saturation levels varied seasonally in accordance with spill schedules. During February and March spill was low and nitrogen saturation levels were normal at 100-105%. Spills increased in April and the saturation levels ranged from 110 to 132%. Peak spilling and saturation levels occurred in June and August (120 to 140%), and then declined into the fall. At Ice Harbor Dam, spilling and saturation levels peaked by mid-May and had declined by mid-June.

In the 1966 study, nitrogen supersaturation conditions were confirmed to exist in the Columbia and Snake rivers, but little incidence of gas bubble disease or mortalities of fish were observed. Events in 1968 at John Day Dam, however, illustrated the potential hazards to salmonids of supersaturation conditions (Beiningen and Ebel 1970). John Day Dam was closed in April of 1968, but because the powerhouse was not operational the entire river flow was passed over the spillway. John Day Dam reservoir also created water temperatures

1 to 2°C higher than existed prior to impoundment of this section of river. This resulted in nitrogen saturations of over 125% from April through September, a much longer period than supersaturation conditions normally occur in the Columbia River. Coincidental to the high spills, pump malfunctions at The Dalles Dam, and insufficient flows through the fishways at John Day Dam caused delays of large numbers of spring and summer chinook salmon, sockeye salmon, and steelhead at these dams. The steelhead were delayed at least one month on their arrival to Ice Harbor Dam. Delays of salmon and steelhead under high water temperatures and supersaturation conditions resulted in large numbers of dead fish observed floating downstream from The Dalles and John Day dams. It was estimated that 20,000 summer chinook salmon were lost during this period. Tissue samples from steelhead and chinook salmon confirmed the presence of gas bubble disease.

Nitrogen saturation levels were again monitored in the Columbia and Snake rivers in 1970, from Little Goose Dam to Astoria (Ebel 1971). Concentrations in the lower Columbia River were lower than in 1968-69, but saturations were higher in the Snake River. Nitrogen saturations downstream from Little Goose Dam were measured at 129% in April and 146% in June. Nitrogen saturation levels dropped quickly after 21 July, concurrently with the decrease of spill at Little Goose Dam from 70 kcfs to 13 kcfs. Levels were back to normal by mid-August. There was some evidence of the effects of the supersaturation levels on adult migrants, as seen by the dead chinook salmon found between Little Goose and Lower Monumental dams in July, some of which

showed symptoms of gas bubble disease. About 30% of the adult fish that returned to Rapid River Hatchery in July also showed symptoms of gas bubble disease.

During a comprehensive review of the information related to nitrogen supersaturation and salmonid migrations in the Columbia and Snake rivers, Ebel et al. (1975) stated that adult salmonids may be able to avoid lethal saturation levels by swimming deeper in the water column, below the critical zone. But when these fish arrive at dams they must pass through the shallow (6-7 ft) fishways where they will be exposed to potentially lethal conditions. Spillway deflectors, which prevent deep plunging of spilled water, were recommended as the effective method to reduce nitrogen saturation levels at Columbia and Snake river dams.

Gray and Haynes (1977) reported evidence that chinook salmon would swim deeper in the water column during supersaturation conditions in the Snake River. In the spring of 1976, chinook salmon with radio transmitters that were tracked as they approached Little Goose Dam generally swam at depths of 2 m. Nitrogen concentrations at this time were high (124-128%), but were below chinook salmon tolerance levels below 1.5 to 2 m depths. When nitrogen concentrations were lower, in the fall of 1976 and spring of 1977, the tagged fish swam significantly closer to the surface.

Other Factors

Pollutants released from river-side industry may also delay salmonid migrations. In a study to determine if the

discharge from an aluminum plant located upstream from John Day Dam was related to delays of salmonids crossing the dam, Damkaer (1983) reported delays that averaged 158 and 156 h during the springs of 1979 and 1980, respectively, delays that were longer than at other dams at that time. Water samples were collected and analyzed from 16 sites around John Day Dam in 1982. Fluoride concentrations in the forebay were 0.2 to 0.5 ppm in April and June, versus a normal level of 0.1 ppm. Median passage times for chinook salmon at John Day Dam in the fall of 1982 were about one week, and Damkaer and Dey (1985) reported "losses" between John Day and McNary dams averaging 55%.

Water samples were collected again in 1983, focusing on the fluoride and heavy metals; cadmium, copper, lead, and zinc (Damkaer and Dey 1984). Fluorides concentrations were about one fourth those measured in 1982, because of a new treatment waste system used at the aluminum plant in 1983, except during September and October when the new system malfunctioned. Losses of fall chinook salmon between John Day and McNary dams had decreased to 11% in 1983 (Damkaer and Dey 1985). Flume studies were conducted in 1983 at Big Beef Creek to test the avoidance of chum, coho, and chinook salmon to 0.5 ppm fluoride concentrations. During these tests the fish were exposed to two flumes, one with fluoride added, and the other with normal water. About half the chinook salmon tested would not move up either flume, but of those that did, 75% chose the

channel without fluoride. Of the coho salmon tested, 36% of the fish moved up the flume, and 66% of those chose the non-fluoride channel. More of the chum salmon moved up the channels (78%), and 60% of those moving upstream chose the non-fluoride channel.

In 1984, fluoride concentrations in the forebay of John Day Dam were usually at 0.1 to 0.2 ppm. The median passage time for chinook salmon to cross the dam was 40 h, and the losses between John Day and McNary dams were similar to 1983 levels (Damkaer and Dey 1985). Experiments were again conducted at Big Beef Creek. In these studies chinook and coho salmon were exposed to two channels, one with a fluoride level of 0.2 ppm, and the other with normal water. Of the 97 chinook salmon, and the 51 coho salmon tested, no preference was shown for either channel.

The effect of chemicals added to the rivers (like fluorides) and electrical fields at the dams and along the power transmission corridors could affect the homing ability of salmon, although there is no evidence of homing disruption from those factors at this time. The discovery of seemingly organized magnetic particles in the head tissue of salmon (Mann et al. 1988) gives rise to speculation that the particles may play a role in orientation and homing of fish and other organisms. Additional work is needed to determine if the particles play a role in homing, and if the role can be disrupted by external factors, such as the electrical fields near dams.

"Losses" During Migration

Although we have no estimates of fish losses and migration delays before dams were constructed in the Columbia and Snake rivers, most people would agree that losses occurred and migration was delayed under certain conditions. Since the counting of fish began at the dams, discrepancies in counts between dams have been noted and several studies have been conducted to determine what proportion of the discrepancies were losses versus fish that could be accounted for at hatcheries, harvest in fisheries, and spawning in tributaries.

The discrepancies in counts of adult salmon and steelhead between dams is usually a case of fewer fish counted at the upstream dam. The percentage of fish that passed over McNary Dam and could not be accounted for at either Priest Rapids or Ice Harbor dams from 1962 to 1978, for example, ranged from 0 to 51% of the count at McNary Dam for spring and summer chinook salmon, and from 9 to 45% for steelhead (Junge 1966a; Stuehrenberg et al. 1978; Bjornn and Ringe 1980). The fate of the unaccounted for fish could include turnoff into tributaries between the dams, harvest by fishermen, spawning in the river between the dams (for some species), errors or incomplete counts at the dams, fallback at dams, and death of the fish between the dams. In some cases a portion of the discrepancies were caused by fallback of fish over one of the dams which caused the counts, if not adjusted, to be erroneous. Whatever the cause, the losses in some instances,

whether natural or human-caused, have been high enough to be of concern.

Potential losses of fish destined to enter the Snake River were first evaluated by Junge (1966a) who compared fish counts at McNary, Priest Rapids, and Ice Harbor dams. From his analysis of the 1962-66 fish counts, Junge concluded that the numbers of spring, summer, and fall chinook salmon and steelhead counted at McNary Dam that could not be accounted for at Priest Rapids or Ice Harbor dams were relatively large, were mostly losses, and the losses were primarily from stocks originating in the Snake River. In that early period, 27-41% of the spring chinook salmon, 8-27% of the summer chinook salmon, and 0-51% of the fall chinook salmon were not accounted for between the three dams. The potential losses of steelhead ranged from 29-45% of the count at McNary Dam in the same area. At that time Junge (1966a) was concerned that there might be a trend toward higher losses.

The causes for the losses in the McNary-Ice Harbor area were attributed by Junge (1966a) to high flows and spill for spring and summer chinook salmon, and high temperatures of the Snake River for steelhead. Evidence was presented that high uniform spill from spillbays 2-9 at Ice Harbor dams resulted in fewer fish passing the dam. For summer chinook salmon, high losses occurred during periods of lower spill and flow. Use of improved spill patterns (i.e. a crowned vs a uniform spill pattern) at Ice Harbor Dam tended to

decrease losses (Junge 1966a; 1966b; 1967).

In a similar analysis of steelhead counts from 1962 to 1979, Bjornn and Ringe (1980) reported an average annual discrepancy of 30% (26,100 fish) between the counts at McNary versus Priest Rapids and Ice Harbor dams. After turnoffs into tributaries and hatcheries in the McNary pool were subtracted, the discrepancy still amounted to 26% of the count at McNary Dam. Bjornn and Ringe (1980) came to the same conclusion as Junge (1966a), that most of the unaccounted for steelhead were Snake River fish. During 1978, Bjornn and Ringe (1980) tracked 176 adult steelhead with radio transmitters to investigate areas of loss and delay within the McNary pool. In that year, the discrepancy between counts at the three dams was 8.6%, the lowest level on record, but discrepancies were high downstream from McNary Dam. No major area of loss was found in the 1978 tracking of steelhead. "Losses" between dams may be due to the cumulative effect of several factors acting on the fish throughout their migration. Probable sources of mortality discussed by Bjornn and Ringe (1980) included injuries from the downstream gill net fishery, heat stress, and delays at the mouth of the Snake River and Ice Harbor Dam. Other sources of mortality include illegal or unreported harvest, and death from injuries from seal bites and sport fishing activities. Unaccounted for losses associated with dams have primarily been attributed to fallback, counting error, and mortalities from physical injuries and stress incurred while crossing dams (Fredd 1966; Stuehrenberg et al. 1978).

Stuehrenberg et al. (1978) tracked spring and summer chinook salmon and steelhead with sonic transmitters in the lower Columbia and Snake rivers during 1967 and 1968. They found that the sport fishery recaptured about 23% of the tagged spring chinook salmon released, 10% of the summer chinook salmon, and 29% of the steelhead. Count discrepancies between McNary and Ice Harbor-Priest Rapids dams during the study period were 15% for spring chinook salmon (1968 only), 7% for summer chinook salmon, and 17 to 35% for steelhead. No other specific areas of loss could be identified.

In a recent analysis of fish counts between McNary, Priest Rapids, and Ice Harbor dams (Bjornn and Rubin 1992), "loss" rates had not gone higher, the losses still appeared to be mainly fish of Snake River origin, and the Snake River fish made up a smaller percentage of the fish counted at McNary Dam. In the 1962-1973 period, the count of spring chinook salmon at Priest Rapids Dam ranged from 8 to 20% of the count at McNary Dam. Since 1973, the annual count of spring chinook salmon at Priest Rapids Dam has ranged from 25 to 50% of the count at McNary Dam, reflecting an increase in the number of fish passing Priest Rapids Dam (mean = 8,700 fish 1963-1973 versus 14,300 fish 1974-1989) and a decrease in the number going up the Snake River (mean = 38,600 fish 1963-1973 versus 24,000 fish 1974-1989). For steelhead, the discrepancies were lower in most of the latter years, but the unaccounted-for-fish still appeared to be mostly Snake River fish.

In a study of passage conditions at Little Goose and Lower Granite dams in

1981, Turner et al. (1983) tracked spring chinook salmon with radio transmitters from Lower Monumental to Lower Granite dams until 19 June. Of 39 fish released at Lower Monumental Dam from 23 April to 1 June, 1 moved up to the mouth of the Tucannon River, 27 moved up to the tailrace of Little Goose Dam, 22 eventually crossed the dam, and 1 moved back downstream to the mouth of the Tucannon River. Of the 22 fish passing Little Goose Dam, 1 fell back over the dam and was later found at the mouth of the Tucannon River, and 21 moved up to Lower Granite Dam, with all 21 crossing over that dam. Assuming that the three fish located at the mouth of the Tucannon River were destined to ascend that stream, there was no loss of radio tagged fish between Little Goose and Lower Granite dams. The 12 fish that could not be accounted for as entering a stream or crossing Little Goose Dam may have included fish that died, fish that regurgitated transmitters, and fish that may have moved upstream after the cessation of surveillance.

Spring chinook salmon were outfitted with radio transmitters and tracked from Hood Park to Ice Harbor and Lower Monumental dams during a 1982 evaluation of the fish passage facilities at the two dams (Turner et al. 1984). Of the 31 fish released at Hood Park, 1 died, and 30 moved the 14 km up to Ice Harbor Dam and then crossed the dam. Of the 30 fish passing over Ice Harbor Dam plus 4 fish released in the Ice Harbor Dam forebay, 31 moved up to Lower Monumental Dam, and 28 crossed the dam. Three of the fish that did not cross Lower Monumental Dam moved back downstream over Ice Harbor Dam, perhaps after deciding they were in the wrong stream. If all of the

unaccounted-for-fish died, the mortality rate for passing the two dams would have been 11% (4 of 35 released).

By comparing the ten-year count averages from Ice Harbor and Lower Granite dams we estimated average annual count discrepancies of 19.9% for spring and summer chinook salmon, and 6.8% for steelhead for this stretch of river during the period 1980-1989 (Annual Fish Passage Report, U.S. Army Corps of Engineers 1989). Based on these values, which do not include adjustments for tributary escapement or sport fishery harvests, the losses of adult salmon and steelhead between Ice Harbor and Lower Granite dams may be less than those reported for the McNary-Priest Rapids-Ice Harbor dam area (Junge 1966a; Bjornn and Ringe 1980).

In an early study of fish count discrepancies between dams, Fredd (1966) analyzed data from 1957 to 1965 from Bonneville, The Dalles, McNary, and Ice Harbor-Priest Rapids dams. Fredd adjusted counts at Bonneville Dam for returns to hatcheries, commercial fishery harvest, and escapements to the Wind River, a tributary in the Bonneville pool, before comparing counts at the upstream dams. Despite the adjustments, the counts at the upstream dams were significantly less than the adjusted counts at Bonneville Dam. For spring chinook salmon, the discrepancy amounted to 20% of the run between the first two dams, 30% between Bonneville and McNary dams, and 54% between Bonneville and Ice Harbor-Priest Rapids dams. For summer chinook salmon, 34% of the run could not be accounted for between Bonneville and the upper two dams. The discrepancy in

counts of steelhead was small between Bonneville and The Dalles dams (3%), but increased to 17% at McNary Dam, and 54% at the upper two dams. Fredd concluded that fishery harvest and escapements to tributaries between the dams was insufficient to account for the discrepancies and that significant numbers of fish were dying enroute to the spawning grounds.

Mortalities at Columbia River dams reported from studies conducted from 1955 to 1978 have ranged from 4% to 26% for chinook salmon (Weiss (1970); Merrell et al.(1971); Gibson et al. 1979; Young et al. 1978), and up to 29% for sockeye salmon in 1954-55 (French and Wahle 1966). Mortalities may be caused from delays below dams, gas supersaturation (up to 120-140% of normal), and physical injuries incurred while crossing dams (Merrell et al. 1971). Injuries to chinook salmon increased by 5% to 20% between Bonneville and Little Goose dams during a study conducted from 1973 to 1975, but the injuries could not be linked to losses between the two dams (Gibson et al. 1979). Steelhead with injuries increased by 18-21% between Bonneville and McNary dams during a 1974-75 study (Young et al. 1978). An extreme example of mortality occurred in 1968 at John Day

Dam (then under construction) when high spills and supersaturation levels combined to produce an estimated 20,000 chinook salmon mortalities, with a resultant 32% loss at McNary Dam (Haas et al. 1969; Haas et al. 1976).

Liscom and Stuehrenberg (1983) reported that 47% of the fall chinook salmon they tracked from Bonneville Dam did not make it over McNary Dam; 24% stayed in the Bonneville pool, 22% in The Dalles pool, and 7% in the John Day pool. Most of the fish entered tributaries or were believed to have spawned in the Columbia River, were caught in commercial and sport fisheries, and fell back over the dams.

Discrepancies in the counts of salmon and steelhead between Columbia and Snake river dams, at first thought to be puzzling, now appear to be the combination of several factors, natural and human-made, acting on the upstream migrants. Upon completion of their study tracking fall chinook salmon from Bonneville to McNary Dam, Liscom and Stuehrenberg (1983) concluded that no major source of losses existed, but that discrepancies were primarily related to difficulties in estimating tributary escapements, main channel spawners, and fishery harvests.

Discussion

Chinook and sockeye salmon and steelhead migrating to spawning grounds and hatcheries in the Snake River drainage must pass over four dams and through their reservoirs in the lower Snake River in addition to the four dams in the lower Columbia River. Several studies

and numerous observations have been made in the last 50 years to aid in the design of appropriate fish passage facilities and guide operations at the dams to make upstream passage as efficient as possible. The adult passage system in the lower Snake River has evolved through the

years in response to the knowledge and experience gained during a variety of flow and operating conditions. The precariously low abundance of sockeye salmon and recent downward trend in chinook salmon numbers spurred the initiation of the basin-wide study of adult migrations in the Snake River to insure that adult passage was not significantly delayed at the dams or other points along the migration route.

The timing of upstream migrations and losses during migration under natural conditions varied annually with flows, turbidities, temperatures, and condition of the fish. The addition of dams and reservoirs to rivers that are the migration routes of salmon and steelhead usually increases the migration time and, in some cases, the mortality of upstream migrants. In the Snake River, before impoundment, and its major tributaries, spring and summer chinook salmon migrated at mean rates of 18-24 km/d (Oregon Fish Commission 1960b). Migration of chinook salmon through the lower Snake River reservoirs has been recorded at mean rates as high as 62 km/d (Turner et al. 1983; 1984; Bjornn et al. 1992), but when time to pass the dams is included, the mean rates of passage were in the 8-22 km/d range (McMaster et al. 1977; Gibson et al. 1979; Bjornn et al. 1992), a little slower than migration rates in unimpounded rivers. When flow conditions are unfavorable for passage of fish at dams (high flows and spill), the migration rates in impounded and unimpounded rivers will decrease.

High flows that occur in the spring, that are often more turbid than at other times of the year, appear to have some effect on migration rates of adult chinook salmon,

but we could not find an example that was not confounded by passage at a dam. The time fish take to pass a dam ranges from a few hours to several days (Table 1). Delay at Little Goose Dam in a year of high flows was twice as long as in a year with low flows (Haynes and Gray 1980). At Lower Granite Dam, the delay in passing the dam averaged about 1 day when flows were relatively low (spill 0-25 kcfs), but nearly 7 d when flows were higher (spill 25-150 kcfs) (Turner et al. 1983).

Discharges from the powerhouse and spillway influence the routes fish use to enter the fishways. When there is no spill, few fish enter the fishways adjacent to the spillway. Small to moderate amounts of spill attract fish to the fishway entrances near the spillway, but large amounts of spill can create turbulence that block the entrances. The pattern of water released over the spillway can influence the flow patterns in the tailrace, the attraction flows leading to the fishway entrances, and the efficiency of fish passage. Although definitive tests are difficult to conduct, limited tests and observations (Junge 1966a; 1967; 1969; Junge and Carnegie 1972; 1976a) have been useful in setting general guidelines for spill patterns at the Snake River dams. With limited spill, the water should be discharged through the end bays to attract fish to nearby fishway entrances. As the quantity of spill increases, discharge from the end bays is kept low to prevent blocking of the entrances adjacent to the spillway, and this gradually leads to a crowned or level spill through the center bays. At high levels of spill (>60 kcfs at the Snake River dams) effective fishway attraction flows become difficult to maintain.

Fishway entrance use by adult salmon and steelhead is influenced by discharges from the powerhouse. The location of entrances and flow patterns differ at each dam, and generalizations are not of much help except to know that fish usually go where there is flow, unless there is too much turbulence. If there is evidence of significant delay at a dam, then a detailed study of entrance use and flow patterns may be needed.

Fluctuations in discharges from powerhouses because of hydroelectric power peaking can delay adult salmon and steelhead in their migration (Junge 1971), may cause an increase in the mortality rate (Young et al. 1974; 1977), and may disrupt the normal daily pattern of migration (Wagner 1971). The influence of reducing flows to zero at night in the Snake River on adult passage were conflicting. McMaster et al. (1977) reported that zero nighttime flows had no measurable effect on the migration rates or behavior of chinook salmon and steelhead in the lower Snake River during a 1975-76 study. Liscom et al. (1985), on the other hand, reported that steelhead traveled slower upstream between Lower Monumental and Little Goose dams in 1981 during zero flows than during normal flows. Some downstream movement during zero flows at night was also seen. Additional testing of the effects of zero flow at night on the migration of steelhead in the lower Snake River was initiated in 1991 and will continue through 1994.

Fishway entrances and ladders at the Snake River dams benefitted from the design and testing at previously constructed dams in the Columbia River. Once adult salmon and steelhead enter the

fishways, some may go out an entrance, but many pass up through the fishways in a few hours. A large proportion of the time required to pass a dam appears to be the time used to find and enter the fishways (Liscom and Monan 1976). Most fish pass through the fishways during daylight (Fields et al. 1963; 1964; Calvin 1975), and those that enter at night usually take longer to pass (Shew et al. 1985). The 1 on 10 slope ladders with overflow weirs and submerged orifices appear to function adequately for adult salmon and steelhead.

Fallback of fish over the spillway or past the turbines after they have crossed a dam varies with species, season of year, flow, and configuration of the components of the dam (Table 2). Fallback rates for spring and summer chinook salmon at the lower Snake River dams appear to be relatively low (<10%) during low flow conditions with no spill, but can be high (40% observed) when large amounts of water is spilled. Fallback rates at the Snake River dams for steelhead seem to be high (up to 20%) considering the low flows and lack of spill during the summer-fall migration period. The natural tendency for many of these fish to overwinter in the lower Snake River is probably an explanation for the high fallback rates. Most of the fish observed to have fallen back at Snake River dams have reascended and continued their migration, which is evidence that falling back over or through a dam is not necessarily fatal. As we learn more about fish migrations in the Columbia and Snake Rivers, we will probably find that some of the fallback is necessary as wandering fish correct their course and resume migration to their natal streams.

The loss of adult salmon and steelhead as they migrate up the Columbia and Snake rivers to natal streams is a major concern. Fish no doubt died during their upstream migration before dams were present, but there are no estimates of the loss. With the addition of dams, the potential for increased loss rates of upstream migrants exist if fish have difficulty passing over a dam or fall back at one or more dam. In an early analysis of potential "losses" between dams, Fredd (1966) reported that the discrepancy in counts between Bonneville and Priest Rapids-Ice Harbor dams for the 1957-65 period averaged 54% for spring chinook salmon, 34% for summer chinook salmon, and 54% for steelhead. He concluded that unreported fishery harvest and escapements to tributaries between the dams was insufficient to account for the discrepancies and that significant numbers of fish were being lost. Junge (1966a) in an analysis of the 1962-66 fish count discrepancies between McNary and Priest Rapids-Ice Harbor dams concluded that substantial losses were occurring and that the losses were primarily fish destined to enter the Snake River. In a recent analysis of the fish count discrepancies for the same area (Bjornn and Rubin 1992), the discrepancies have not gone higher and the "losses" still seem to be mostly of Snake River fish. Liscom and Stuehrenberg (1983) after radio tracking fall chinook from Bonneville to McNary dams concluded that fish count

discrepancies at the dams were not losses, for the most part, but due to our lack of information on tributary escapements, main channel spawners, and fishery harvests.

In contrast to Liscom and Stuehrenberg's (1983) conclusion that few fall chinook salmon were lost between Bonneville and McNary dams, losses of adults can be significant as they migrate upstream. In studies where mortality was monitored, losses of adult chinook salmon and steelhead while passing dams have ranged from 4 to 29% (French and Wahle 1966; Gibson et al. 1979; Merrell et al. 1971; Weiss 1970; Young et al. 1978). Losses of the magnitude listed above may not occur now because of improvements in facilities and operations in recent years. Nevertheless, losses can be significant as in 1991, when up to 25% of the spring and summer chinook salmon released at Hood Park near the mouth of the Snake River with radio transmitters could not be accounted for upstream from the reservoirs (Bjornn et al. 1992). Conditions for upstream migration of adults were relatively good in 1991 (low flows, no spill, low turbidity) and no obvious passage problems were encountered. Many of the lost fish may have died from natural causes. The effect of less optimum migration conditions on adult survival rates in the Snake River will be studied in future years, and means of reducing the losses of adults, from whatever cause, should be pursued.

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